The Energy and Resources Institute
Creating Innovative Solutions for a Sustainable Future

Energy Efficiency Options in Electric Arc Furnaces

Best Practices and Technologies

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Foreword

The Indian steel industry plays a pivotal role in the country's economic growth and industrial development. As one of the world's largest steel producers, India faces the dual challenge of increasing production capacity while aligning with national and global decarbonization and sustainability goals. As the steel sector contributes significantly to greenhouse gas emissions, improving energy efficiency and adopting cleaner technologies have become imperative to ensure a sustainable future.

Electric Arc Furnaces (EAFs) are gaining prominence as an energy-efficient and lower-emission alternative to traditional steelmaking processes. As India moves towards increased steel production through EAFs, optimizing their energy performance is crucial for reducing costs, minimizing environmental impact, and enhancing competitiveness. Implementing best practices and innovative technologies in EAF operations can significantly lower energy consumption and emissions, thereby supporting the country's broader commitment to carbon neutrality.

This report titled, ***Energy Efficiency in Electric Arc Furnaces – Best Practices and Technologies***, provides a comprehensive analysis of key strategies to improve EAF performance. It highlights proven technological interventions and operational optimizations that can drive efficiency gains. By adopting these practices, the steel industry can contribute meaningfully to India's energy transition while ensuring economic viability.

At The Energy and Resources Institute (TERI), we remain committed to advancing energy efficiency and promoting sustainable industrial practices. Through rigorous research, policy advocacy, and capacity-building initiatives, TERI continues to support industries in their journeys towards decarbonization. We hope this report serves as a valuable resource for policymakers, industry stakeholders, and researchers striving for a cleaner and more energy-efficient steel sector.

We appreciate the contributions of experts, industry leaders, and researchers who have collaborated on this report, and we look forward to continued engagement in shaping a sustainable future for steelmaking in India.

Dr Vibha Dhawan

Director General
TERI

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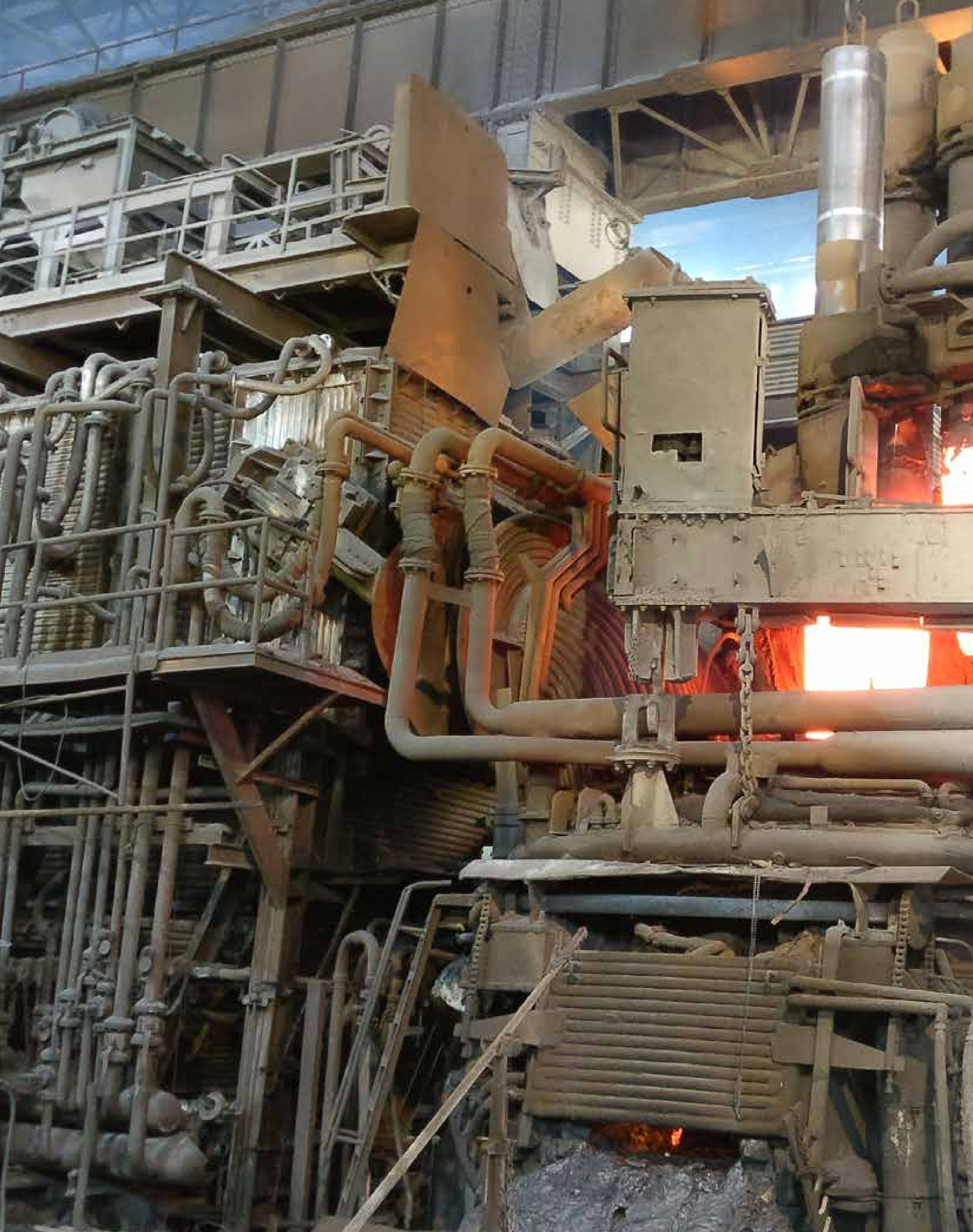


01

Introduction

In 2023–24, India's crude steel production was 144 million tonnes (Mt) or 7 percent of global production. It is currently the second-largest steel producer and consumer in the world. The building construction sector is the largest consumer of steel in the country, followed by infrastructure, automobiles, and appliances.

Steel production is estimated to increase to 255 Mt by 2030–31 (NSP, 2017). Government policies such as Pradhan Mantri Awas Yojana, or Housing for All, Smart Cities mission, and investment in ports, railways and other large infrastructural projects are expected to drive the demand for steel in the coming years (PMAY (U), 2015, Interim Budget, GoI, 2024).

The steel sector is the single largest energy consumer and largest emitter of carbon dioxide (CO_2) in the industrial sector. The sector consumes enormous quantities of coal and consequently emits large volumes of CO_2, a greenhouse gas. Hence, cutting down carbon emissions in the sector, by improvements in energy efficiency is an important lever towards decarbonization. This chapter describes the major steel production routes, discusses the capacity and production of steel through EAF route and reviews the carbon intensity of steel produced using this route.

1.1

Steel production routes

The sector is heterogenous as compared to other countries—there are seven large-scale integrated steel producers and many small and medium scale producers. The steel produced can be broadly categorized into three categories based on their steelmaking process routes—basic oxygen furnace (BOF), electric arc furnace (EAF) and induction furnace (IF). The BOF route is used by 'primary' steel producers or integrated steel plants (ISPs). The EAF and IF routes are used for 'secondary' steel production. The EAF route is used by both ISPs and medium scale steel producers to make value added speciality steel grades. The IF route is commonly used by small and medium scale steel producers making TMT rebars widely used in construction sector in India. Figure 1 shows the route-wise share of steel produced in India (JPC 2024).

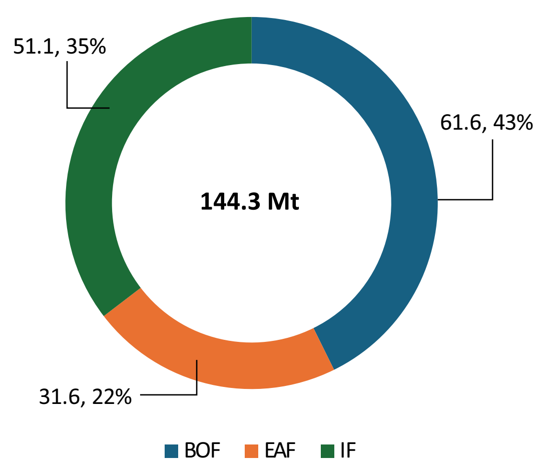


Figure 1: Route-wise steel production (Mt)

Source: JPC 2024

1.2

EAF route steel producers

There were 39 EAF route steel producers in India (JPC 2024). About 32 Mt of crude steel was produced through EAF route in 2023–24. Maharashtra, Odisha, Chhattisgarh and Gujarat have the largest production of EAF based steel. The state-wise distribution of EAF steel producers and steel production are shown in Figure 2 and Figure 3, respectively. A detailed list of EAF units is given in Annexure 1.

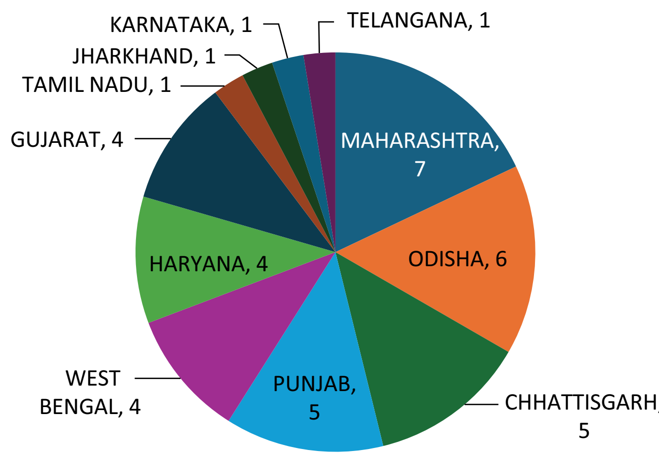


Figure 2: State-wise EAF steel producers

Source: JPC 2024

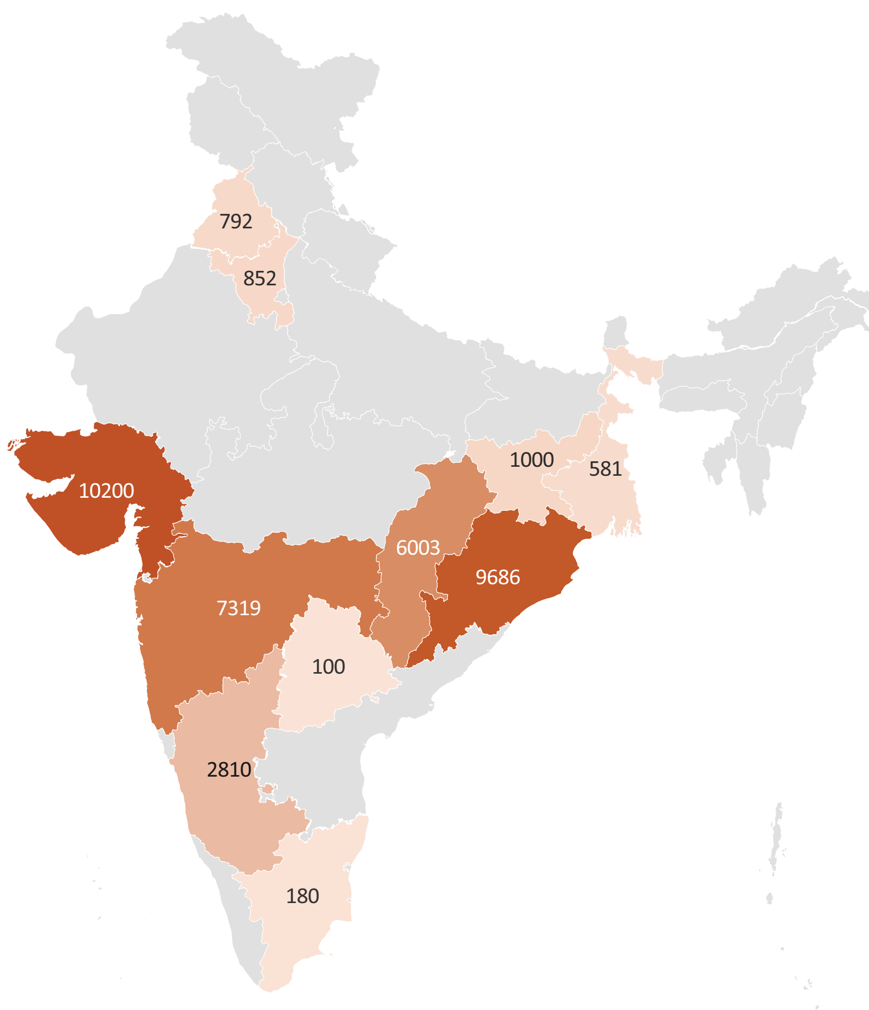


Figure 3: State-wise steel production using EAF route (in ttpa), 2023–24

Over the years, capacity of steel through EAF route has remained almost the same. Figure 4 shows the production of steel through the EAF route in the last 5 years.

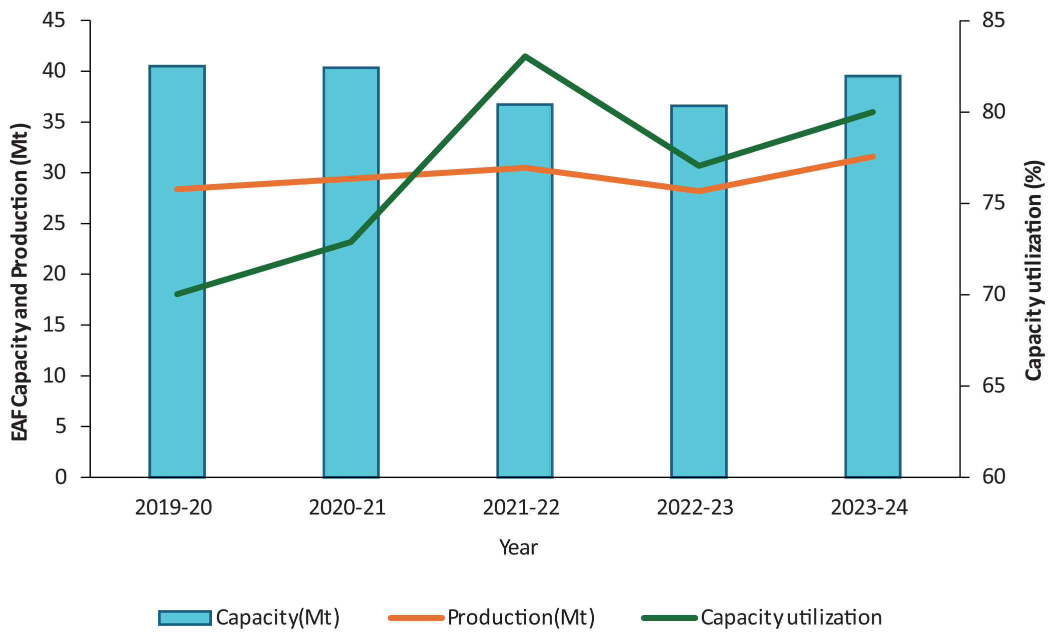


Figure 4: Installed capacity, production and capacity utilization of EAF route in India

Source: JPC, 2024

Table 1 shows the steel production of major EAF producers in India.

Table 1: Production major EAF steel producers in India (Mt)

Company	2019–20	2020–21	2021–22	2022–23	2023–24
SAIL	0.21	0.158	0.21	0.237	0.261
Tata Steel	2.126	1.392	2.249	2.29	2.448
AM/NS India	7.121	6.696	7.295	6.688	7.683
JSW Steel@	6.329	6	7.643		
JSW Group				9.387	11.079
JSPL	5.861	6.859	4.963	4.786	5.020
Others	6.719	8.301	8.138	4.815	5.121
Total EAF	28.366	29.407	30.498	28.203	31.612

@ Merged to JSW Group in FY 2022–23

Source: JPC 2024

Some of the major EAF producers like JSW Steel and AM/NS India use large capacities of EAFs (between 100 to 250 tonnes) which are comparable to international standards. The adoption of large EAF capacities by major producers has been mainly to meet the growing demand of high-quality steel grades. However, there is a large number of small and medium scale steel producers use mini-EAFs. Table 2 provides the furnace capacities of mini-EAFs used by secondary steel producers and the rating of transformers used by these units.

Table 2: Furnace capacities of small and medium EAF producers and transformers capacities

Category	Capacity, tonnes	Power transformer, MVA
A	15	7.5
B	25–35	24–32
C	40–50	40

Source: TERI database

1.3

Energy consumption and carbon intensity of EAF producers

Electricity is the major source of energy in an EAF. The specific energy consumption (SEC), also called energy density, is the amount of energy required to produce a tonne of steel. The SEC of an EAF varies widely due to differences in capacity, vintage, power transformer, operating practices, charge mix, grade of steel produced and so on. Energy audits done by TERI among small and medium EAF producers show that there is a large variation is the SEC of the furnace. The SEC ranged between 415 kWh to 675 kWh (1.49 GJ to 2.43 GJ) (TERI database, 2017).

The GHG emission intensity (or carbon intensity) of steel production is the measure of greenhouse gas (GHG) emissions in the crude steelmaking process. It is measured in tonne CO_2 per tonne steel (tCO_2/t steel). Typically, Scope 1 and Scope 2 GHG emissions are considered while calculating GHG emission intensity. The GHG emission intensity of steel produced by EAF route can vary widely depending upon the raw material charged. For example, the GHG emission intensity for an EAF producer using only recycled scrap as charge is about 0.55–0.65 tCO_2/t, which is roughly 75% lower as compared to steel made from blast furnace route. As a comparison, the GHG emission intensity from coal DRI route is about 3 tCO_2/t, which is roughly 30% higher than steel made from the blast furnace route. Typical GHG emission intensity ranges of different categories of EAF producers in India are shown in Table 3.

Table 3: GHG emission intensity of EAF steel producers

Primary raw material used in steel production	Typical GHG emission intensity range (tCO_2/t steel)
Coal based DRI	2.7–3.1
Syngas based DRI	2.5–2.9
Natural gas based DRI	1.4–1.6
Scrap	0.55–0.65

Source: GSI, MoS, 2024

02

Technology and operation of arc furnace

Steel is made by heating and melting metals like iron, steel scrap and ferroalloys (like ferro chromium, ferro nickel, etc.) in desired composition in a furnace. The primary steel producers use iron ore and coke in their blast furnace (BF) to make iron and basic oxygen furnace (BOF) to produce steel. Steel can also be made from direct reduced iron method (DRI). The secondary steel producers produce steel using an electric arc furnace (EAF) or an induction furnace (IF). DRI, pig iron and steel scrap are used to produce steel in these furnaces.

This chapter outlines the technology and operation of EAFs. The comparative advantages of EAF over other steelmaking routes — BOF and IF — are also outlined.

2.1 Technology

The energy required for producing the melt in an EAF is obtained through electric arc between the electrodes. It is a batch melting process producing batches of molten steel known as heat. The EAF operating cycle is called the tap-to-tap cycle.

EAFs are broadly of two types – alternating current (AC) and direct current (DC). Applicable only in large furnace sizes, in DC furnace system only a single electrode is used, and the bottom of the vessel serves as the anode. This arc furnace achieves energy savings of approximately 5% in terms of power consumption in comparison with the older designs of AC EAFs.

Most of the EAFs operated by secondary steel producers in India are small in size and based on 3-phase AC technology. An AC EAF power on and off is achieved through switching of the AC EAF transformer. An AC EAF uses three electrodes to distribute the energy. A cross-sectional view of an AC EAF is shown in Figure 5.

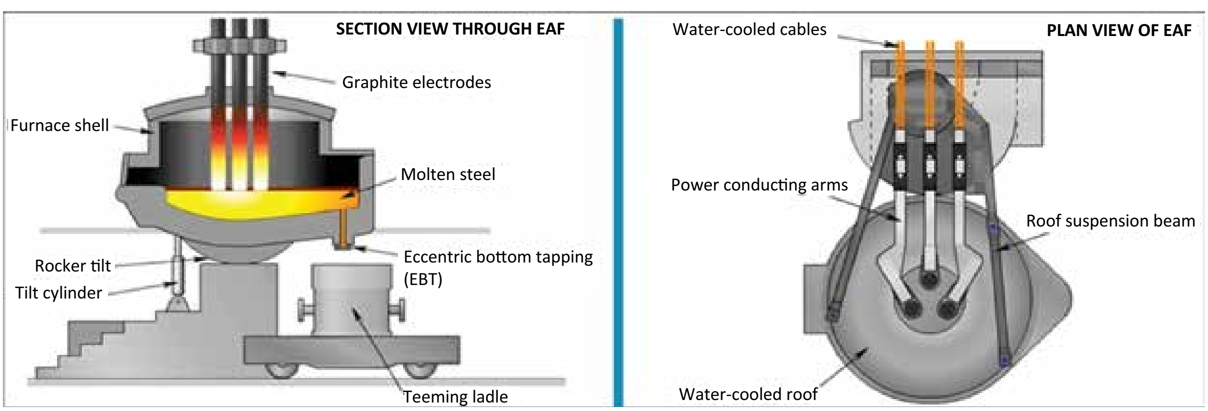


Figure 5: Sectional view of AC EAF

Source: www.steeluniversity.org

The construction of EAF encompasses an outer furnace shell lined internally with refractory materials. The whole structure is mounted on a motorized tilting mechanism. The graphite electrodes enter the furnace from the roof. Modern electrode control systems are automatically controlled and complemented with servo motors for precise electrode movements. The shell, roof and electrodes are water cooled. These furnaces generally have a door for alloying, oxygen lancing and slag removal purposes.

Conventional EAFs have tapping spouts (doors) for pouring out the liquid steel and oxygen lancing is done through the slag doors. State-of-the-art furnaces have eccentric bottom tapping and oxy-fuel burners.

2.2 Operation

The tap-to-tap cycle of an EAF, typically between 60–90 minutes, can be broadly categorized into the following operations.

1. Charge mix preparation and charging
2. Melting
3. Oxidation and refining
4. De-slagging
5. Tapping into ladle
6. Furnace turnaround

2.2.1 Charge mix preparation and charging

The major charge materials are metallics, limestone/dolomite and coke. Typical metallics include pig iron, DRI, heavy scrap, light scrap and plant returns. A typical charge mix in an EAF used by a secondary steel producer is shown in Figure 6. However, the charge mix varies considerably and is a function of the grade of steel produced and the availability/cost of raw materials. The function of limestone/dolomite is to facilitate the formation of slag. The slag entraps various impurities like scale and rust from the melt. Typically, the amount of limestone and dolomite charged is about 5% of the metallic charge. Carbon is charged to provide a reducing atmosphere during melting and minimize oxidation. Typically, the amount of coke in the charge is about 2% of the metallic charge. Several carbon sources, such as anthracite coal, coke, graphite coke or calcined petroleum coke may be used. The charge coke also helps in achieving the desired carbon level in the end product.

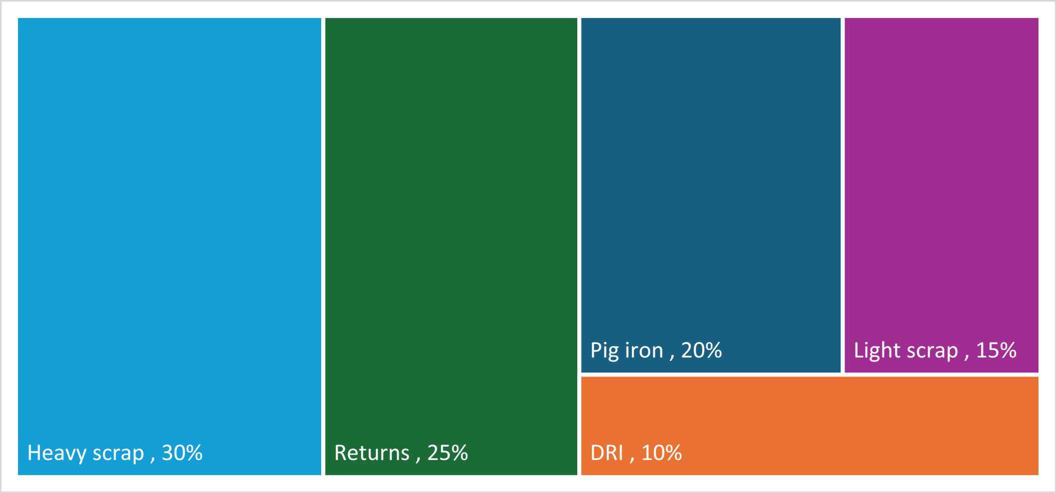


Figure 6: Typical charge mix EAF

Source: TERI database

State-of-the-art large installations include continuous charging of preheated scrap on conveyer belt or from a shaft above the furnace with off-gases directed through the shaft. Hot metal produced in the blast furnace can also be charged.

2.2.2
Melting

Electrical energy which is the major energy input is fed through graphite electrodes. At the start, an intermediate voltage tap is selected until the electrodes penetrate the metallics. Usually, light weight scrap is kept on top of the charge to hasten initial melting and create molten metal pool. Approximately 15% of metallic charge melts during initial period. After few minutes a long arc, i.e., a high voltage tap is used. At the start, the arc is generally erratic and unstable. As the furnace heats up, the arc becomes stable and the average power input rises. Once enough metallics have melted, more metallics are charged. Typical input and output materials in an EAF is shown in Figure 7.

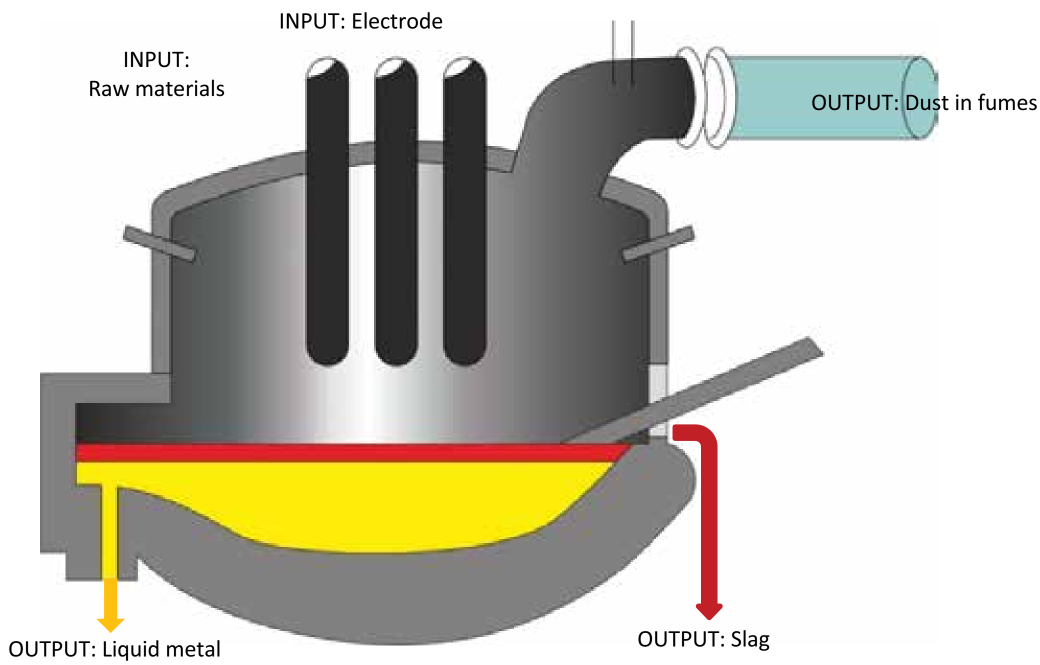


Figure 7: Input and output materials in an EAF

2.2.3
Oxidation and refining

Once the melting starts, oxidation and refining operations take place to correct the steel chemistry by removing impurities. Oxygen is blown into the bath to accelerate the oxidation of impurities present in the steel melt such as silicon, sulphur, phosphorus, aluminium, manganese and calcium and the remaining oxides are transferred to slag, which floats on the surface of the molten steel. These reactions are exothermic and provide additional energy for the melting process. The important exothermic reactions and heat of reaction at 1650°C (ΔH in kWh/kg) are provided in Table 4.

Table 4: Heat of reactions inside EAF

Exothermic reaction	ΔH
$Fe + ½ O_2 (g) → FeO$	1.275
$Si + O_2 (g) → SiO_2$	9.348
$4Al + 3 O_2 (g) → 2 Al_2O_3$	8.650
$C + ½ O_2 (g) → CO (g)$	2.739
$CO (g) + ½ O_2 (g) → CO_2 (g)$	2.763
$C + O_2 (g) → CO_2 (g)$	9.184
$Mn + ½ O_2 (g) → MnO$	2.044
$H_2 (g) + ½ O_2 (g) → H_2O (g)$	34.614
$CH_4 (g) + 2 O_2 → CO_2 (g) + 2 H_2O$	13.994

Source: *P Eugene et al., EAF Fundamentals*

Carbon escapes in the form of carbon monoxide gas and produce 'carbon boil' in the metal. The carbon boil is an essential part of the refining process and helps in heat transfer by agitating the bath, cleansing the bath of retained oxides as slag, accelerating reactions at the gas metal interface and aiding removal of H_2 and N_2.

Phosphorus is removed during oxidation phase period whereas sulphur is removed during reduction phase. The limestone or dolomite added in the process helps in de-slagging. The calcium oxide in limestone reacts with silicon dioxide and forms calcium silicate slag.

$$2\,P + 5\,FeO \rightarrow (P_2O_5)_{SLAG} + 5\,Fe$$
$$(P_2O_5)_{SLAG} + 3\,(CaO)_{SLAG} \rightarrow Ca_3(PO_4)_{2\,SLAG}$$
$$(CaO)_{SLAG} + [FeS]_{BATH} \rightarrow (CaS)_{SLAG} + [FeO]$$
$$(CaC_2)_{SLAG} + 3\,[FeS]_{BATH} + 2\,(CaO)_{SLAG} \rightarrow 3\,[Fe] + 3\,(CaS) + 2\,(CO)_{GAS}$$
$$2\,CaO + 2\,SiO_2 \rightarrow 2(CaO.SiO_2)_{SLAG}$$

The finished slag contains SiO_2, MnO, CaO, FeO and other elements. The slag floats over metal bath and acts as destination for oxidized impurities. It also acts as thermal insulating layer thus reducing excessive heat loss. Slag floats over metal and acts as thermal insulating layer reducing heat losses from melt surface.

2.2.4
De-slagging

De-slagging operations are carried out to remove impurities from the furnace. During melting and refining operations, some of the undesirable materials within the bath are oxidized and enter the slag phase. It is advantageous to remove as much phosphorus into the slag as early in the heat as possible (i.e., while the bath temperature is still low). The furnace is tilted backwards, and slag is poured out of the furnace through the slag door. If the high-phosphorus slag has not been removed before this operation, phosphorus reversion will occur. During slag foaming, slag may overflow the steel level in the EAF and flow out of the slag door.

2.2.5
Tapping

The molten steel is tapped into a pre-heated ladle either by tilting or by EBT mechanism. During the tapping process, deoxidation is carried out using specific deoxidizers having high affinity towards oxygen in the bath as compared to iron. The most common de-oxidizers include ferro-alloys, i.e., ferro-manganese or ferro-silicon. Aluminium is typically added at the end which is the most powerful de-oxidizing agent when compared to ferro-alloys. Slag-forming compounds are added in the ladle at tap so that a slag cover is formed before transfer to the ladle furnace. Additional slag materials may be added at the ladle furnace if the slag cover is insufficient.

Once the required temperature is achieved (usually about 1650°C), a sample is drawn from the bath to ascertain desired chemistry of the molten bath. Finer corrections are made to chemistry if required.

2.2.6 Furnace turn-around

Furnace turnaround is the period following completion of tapping until the furnace is recharged for the next heat. During this period, the electrodes and roof are raised, and the furnace lining is inspected for refractory damage. If necessary, repairs are made to the hearth, slag-line, tap-hole and spout. In case of a bottom-tapping furnace, the taphole is filled with sand. Repairs to the furnace are made using gunned refractories or mud slingers. In most modern furnaces, the increased use of water-cooled panels has reduced the amount of patching or "fettling" required between heats. Many operations now switch out the furnace bottom on a regular basis (2–6 weeks) and perform the hearth maintenance off-line. This reduces the power-off time for the EAF and maximizes furnace productivity. Furnace turnaround time is generally the longest dead time (i.e., power off) period in the tap-to-tap cycle. With advances in furnace practices, this has been reduced from 20 minutes to less than 5 minutes in some newer operations (Jones A.T., Nupro Corporation).

2.3 Power quality

Due to the process of melting and refining metals, the EAFs consume large blocks of power (active and reactive power) causing significant disturbances, such as harmonics and voltage fluctuations (flicker) on distribution networks. The non-linear voltage-current characteristic of the electric arc, the irregularities in the shape of the metal to be melted, and the constant triggering of the electric arc during the melting process, cause low PQ indexes. Electric utilities and industrial facilities that have an EAF, have to make significant efforts to implement technical and economical solutions to mitigate the power quality problems associated with the EAF operation (Marulanda-D J.J. *et al.*, 2023).

2.4 Environmental aspects

2.4.1 Pollution control

EAFs produce particulate emissions. A fume extraction system must be installed to catch the vapour and fine particles. The off-gases, at about 1100 °C, are cooled before they enter the pollution control system (typically a bag filter).

2.4.2
Slag disposal

Slag is generated in an EAF due to the removal of chemical impurities during the refining process. Flux added during the process helps in slag formation. The slag is generally oxidizing or reducing in nature, depending upon the steel grade.

The construction industry has proposed sustainable solutions for the reuse of steel slag. Slag has been used as a replacement for aggregates in concrete owing to its high hardness caused by high iron oxide content. According to some studies, slag can sequester CO_2 (Ilhwan You ***et al.***, 2024).

2.5
Advantages of EAF over other steelmaking routes

Due to its advantages, EAF steel production which accounts for about 30% of global steel production at present, is expected to grow sharply in the future. Some advantages of EAF over BOF and IF are discussed in this section.

2.5.1
Advantages in comparison to BOF

BOF steelmaking uses primary raw materials—iron ore and coking coal—to produce new steel. Iron ore is initially reduced to liquid iron (hot metal) in the blast furnace. The hot metal is then converted to steel in the BOF. About 70% of global steel production is attributed to this method of steelmaking. The major advantages of EAF over BOF steelmaking are as follows.

2.5.1.1
Easier decarbonization pathway

EAF steelmaking has less carbon intensity than primary BOF steelmaking and hence, is an important technological pathway for decarbonizing steel. EAF is the standard method for recycling scrap steel from end-of-life vehicles and industrial equipment. As more steel gets produced from scrap, the use of EAF is expected to rise. Use of scrap steel in EAF significantly reduces CO_2 emissions in comparison to primary steel production from iron ore. Recycling one tonne of steel scrap saves 1.5 t of CO_2 (WSA, 2022). The carbon intensity of the EAF steel production from scrap is 0.56–0.66 tCO_2/t steel (WSA, 2024) which is significantly lower as compared to 2.3 tCO_2/t steel in BF-BOF. With best available technology and zero GHG electricity, a green hydrogen based DRI-EAF plant can also achieve 0.08 tCO_2/t steel (MPP, 2022)

2.5.1.2
Greater flexibility of operation

There is a greater flexibility to use number of raw materials like recycled scrap steel, DRI and hot metal (pig iron) from BF in EAF steelmaking. Also, EAF plants are smaller and less capex intensive compared to integrated BOF steelmaking plants, which are generally only cost-effective at large scales (millions of tonnes per year). EAF steelmaking is also more flexible in terms of scale up and down as per market requirements.

2.5.1.3

Suitability for special grade steel

EAFs are suitable for producing high quality special and alloy steel for critical end-use applications in the automotive, engineering and oil and gas industry. Alloy steel is a type of steel alloyed with several elements such as molybdenum, manganese, nickel, chromium, vanadium, silicon, and boron. These alloying elements are added to increase strength, hardness, corrosion resistance, and toughness. Since the requirements of speciality steel is much low as compared to plain carbon steel EAFs are best suited for their production.

For example, EAFs are suitable for producing ultra-low carbon (ULC) steel grades. These grades, containing carbon as low as 35 ppm or 0.0035%, have advantages like good formability, superior surface quality while maintaining strength. Such grades are soft and malleable and used in a range of applications such as panels in the automotive industry. EAFs can also be used to produce high yield strength steel grades which are suitable for high pressure oil and gas pipeline transportation systems. These grades have stringent requirements for high strength and fracture toughness, necessitating extremely low levels of impurities. The presence of impurities like phosphorus, sulphur, hydrogen, oxygen, and nitrogen must be controlled to ensure the desired properties of strength and fracture resistance.

2.5.2

Advantages in comparison to IF

Globally, BOFs and EAFs have been the preferred steelmaking routes. After commercialization of large capacity Induction Furnaces (IFs) (50–65 tonnes) around mid-2000s, it became an attractive electric melting unit for small steel-melting mills in India. The main raw materials for IF steel mills are steel scrap, sponge iron and cast iron. India is one of the countries where use of sponge iron contributes a large share in annual crude steel production. Majority of the steel produced through induction furnace route is plain carbon steel. The main limitation in maintaining quality of construction steel is controlling the composition in steel produced through induction furnace route especially if sponge iron is used. The steel retains phosphorous in the range of 0.045% to as high as 0.09% depending on the quality of raw materials. Ladle metallurgy is a very important technology when it comes to refining of steel and adjusting the final chemistry. The operations performed in ladles include de-oxidation or "killing", vacuum degassing, alloy addition, inclusion removal, inclusion chemistry modification, de-sulphurization and homogenization of the bath. When these operations are carried out in the ladle, they consume energy. Hence, extra energy needs to be supplied to the ladle. Electrical arcing is one of the ways to provide energy for the ladle operations. LRF (ladle refining furnace) carry out dephosphorization and desulphurization of steel in the ladle (Bedarkar, S 2019). EAF steelmaking process has several advantages over IF steelmaking process, some of which are elaborated further.

2.5.2.1

Greater control over phosphorus, sulphur and carbon

EAF steelmaking process is more flexible due to the possibility of melting and refining process in a single unit along with the capability to control temperature and use different charge mixes. This is helpful in the selective removal of impurities. Phosphorus and sulphur occur normally in the furnace charge in higher concentrations than the permissible limits in the steel and must be removed[1].

1 For reference, AISI 1020 grade steel used in general engineering applications have Sulphur ≤ 0.050 %and Phosphorous ≤ 0.040 % and carbon 0.17 – 0.23 %.

EAF is preferred when phosphorus requirements are less than 0.015%. In an EAF, the higher slag temperature allows dephosphorization and deoxidation process. The sulphur is removed mainly as sulphide dissolved in the slag. The sulphur partition between the slag and metal is dependent on slag chemistry. Desulphurization is effective during the reducing phase of steel. Decarburization is carried out by injecting oxygen through a consumable lance or water-cooled lance to coherent jet burners or injectors on the side walls. The carbon content at flat bath will depend on the recovery of carbon in the charge. The decarburization reaction forms mainly carbon monoxide (CO), which escapes the system. Due to refining capabilities of EAF, it is possible to use lower grade scrap, DRI and pig iron (Danieli, 2024). For IF steelmaking, ladle refining and vacuum degassing after melting may be required to improve the quality of steel.

2.5.2.2
Flexibility to process wide variety of charged materials

EAFs can handle a wide variety of charged materials (scrap, DRI/sponge iron, pig iron). In induction furnaces, the charged material depends on the final grade of the material to be manufactured. Due to absence of refining metallurgical processes in IF, proper selection of charged materials to balance carbon, phosphorus and residual elements is needed.

2.5.2.3
Ability to refine metal

With the ability to use oxygen to remove unwanted materials by oxidizing and melting by electric arc, EAFs have flexibility of both refining and melting. In modern EAF operations, especially those operating with a 'hot heel' of molten steel and slag retained from prior heat, oxygen is often blown into the bath throughout the heat. This technique allows for simultaneous operation of melting and refining in the furnace. Hot heel practice is very beneficial for phosphorus removal, and it is usually carried out as early as possible in the heat. In the process, oxygen is lanced early into the heat when bath temperature is relatively low. Thus, EAFs have advanced capabilities that allow them to produce different steel grades to meet various requirements and can replace imports of steel products in the country.

2.5.2.4
Large furnace capacities

EAFs usually have larger capacities starting from 25 t and can go as high as up to 300 t. One of the largest twin-DC EAF is of 420 t capacity (Danieli,2024). These furnaces are suitable for mass production of quality steel. Typically, IF are of smaller capacities (10–20 t) and so can be more cost-effective for smaller steel melting shops and when in large numbers, often suitable for mass production of lower-grade steel production.

03

Energy audits

In general, most EAFs operating in the small and medium scale sector are old. As a result, large amount of energy is wasted. In order to ascertain the causes and extent of inefficiency in energy use among secondary steel producers, TERI conducts energy audits in EAF units. The energy audits include a detailed material and energy balance of a few melts. Based on the audits, other important performance indicators like capacity utilization of the furnace, yield and SEC are calculated.

3.1 Material balance

For the material balance, data of input and output materials in the furnace is collected for several heats.

The input materials include:

- weight of metallics, viz., pig iron, DRI, light scrap, heavy scrap, and plant returns
- weight of other charge materials, viz., limestone/dolomite, coke/calcined petroleum coke (CPC), and de-oxidizers like ferro-alloys and aluminium
- weight of the electrode consumed

The output materials include:

- weight of liquid metal tapped
- weight of slag
- weight of dust in the fumes/off-gases

For a typical material balance of 12 heats of a 50 tonne EAF, the weight of metallics and other inputs is summarized in Tables 5 and 6.

Table 5: Metallics inputs of an EAF (Example)

	Iron bearing materials (12 heats), tonne	Average metallics per heat, tonne
Pig iron	182.0	15.17
DRI	20.2	1.68
Heavy scrap	296.5	24.70
Plant returns	129.6	10.80
Total metallics	628.3	52.36

Table 6: Other inputs of an EAF (Example)

	Other materials (12 heats), tonne	Average other materials per heat, tonne
Lime/dolomite	6.10	0.51
Coke	7.52	0.63
FeSi	2.08	0.17
Aluminium/Deoxidizer	8.71	0.72
Electrode	2.30	0.19
Total	26.71	2.23

The weight of output materials is summarized in Table 7.

Table 7: Output materials of an EAF (Example)

	Total (12 heats), tonne	Average per heat, tonne
Liquid metal	599.81	49.98
Slag	43.21	3.60
Dust in fumes*	12.00	1.00
Total	655.01	54.58

** Dust in fumes is estimated by balance. It typically varies between 15–25 kg per tonne of liquid metal depending on the quality of raw materials*

The chemical composition plays an important role in imparting the desired mechanical properties like yield strength and tensile strength of the steel. The composition of key elements like carbon, silicon, sulphur, phosphorus and manganese depends on the temperature, furnace operation and the reactivity of these elements and oxygen. Hence, chemical analysis of the input and output materials are important to estimate loss/pick up of key elements, during energy audit of the furnace.

The typical chemical composition and physical properties of TMT Fe 550 rebar are provided in Table 8.

Table 8: Chemical composition and mechanical properties of TMT Fe 550 (as per IS 1786:2008)

Composition (%)	% in Steel
Carbon	0.30
Sulphur (% max)	0.055
Phosphorous (% max)	0.050
Sulphur + Phosphorus (% max)	0.100
Carbon Equivalent (CEQ) (% max)	0.42
Manganese (% min)	0.50
Mechanical properties	
Yield Stress	550 N/mm^2
Tensile Strength	585 N/mm^2

3.2

Energy performance

Energy balance is a powerful tool to identify areas where energy utilization can be improved. The amounts of energy input and output, over an entire tap-to-tap cycle, are estimated during an energy balance. An example of an energy balance for an electric arc furnace is shown in Table 9.

Table 9: Energy balance of an EAF

Energy input			Energy output		
	kWh/t	%		kWh/t	%
Input power	351	50.2	Molten metal	397	56.7
Exothermic oxidation of charged materials	229	32.7	Exhaust gas loss	83	11.8
Fuel combustion	48	6.8	Slag heat loss	59	8.6
Heat of slag formation	14	2.0	Electrical (transformer) losses	26	3.7
Electrode oxidation	23	3.3	Cooling water loss	72	10.3
Other	35	5.0	Roof heat loss	4	0.5
			Other losses	59	8.4
Total	700	100		700	100

Source: JICA, 2009

The energy distribution is greatly dependent on raw material quality and consumables and is unique to the specific melt-shop operation. The oxygen supplied to the EAF will react with several components in the bath including aluminium, silicon, manganese, phosphorus, carbon and iron to form oxides. All of these reactions being exothermic, supply additional heat in the melting process.

The energy outputs are measured or theoretically estimated. Some formulae to calculate the heat losses are provided in Annexure 2.

A Sankey diagram (Figure 8) shows typical amount of input energy and amount of heat in melt and different heat losses. As shown in the figure, heat losses in flue gas (15–20%) and cooling water (8–14%) are the major components of energy loss. The quantum of heat losses clearly shows that there exists a significant potential to improve the energy utilization of an EAF by reducing various heat losses.

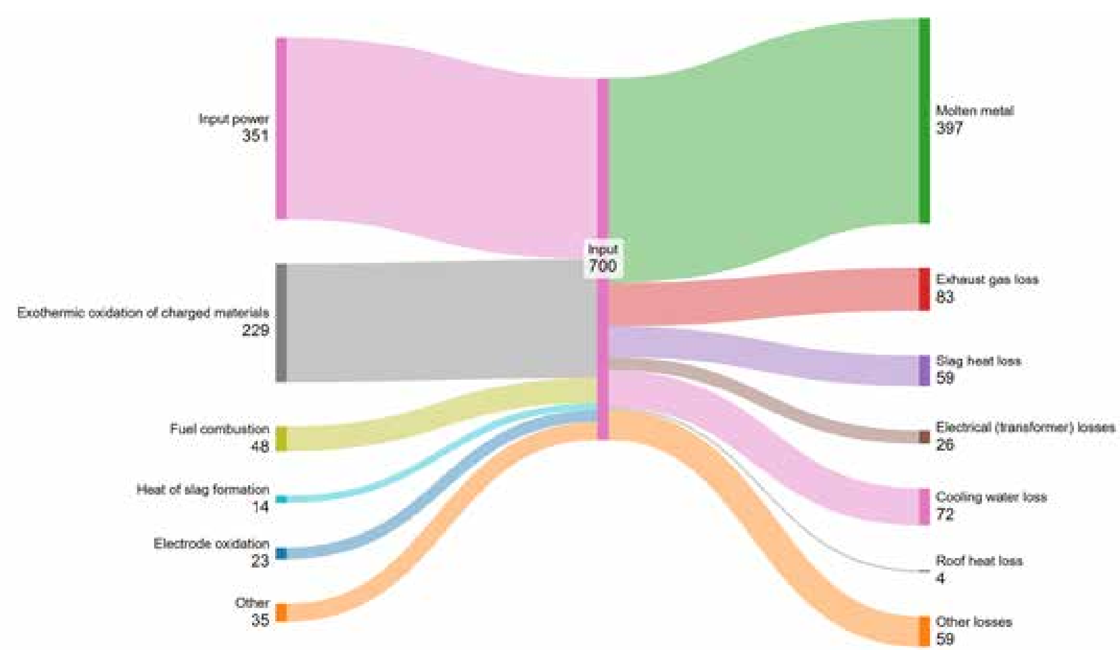


Figure 8: A typical Sankey diagram for an EAF

Source: JICA, 2009

3.3
Energy efficiency

The specific energy consumption (SEC) or the energy consumed per unit mass is a measure of the energy efficiency of furnace. The SEC of the furnace, denoted in kWh/t is the ratio of kWh consumption per tonne of metal. SEC is calculated as kWh per tonne of metallics charged for energy performance evaluation purposes. The power consumption of the ladle furnace, continuous casting mill, auxiliary equipment (cranes, gas cleaning plant), utilities (compressed air, water, oxygen, argon, nitrogen), rolling mills and so on are monitored separately.

The SEC of the furnace is also a function of its capacity. SEC increases with decreasing size of EAF (Figure 9). Close monitoring and control of key operating parameter like temperature of tapped liquid metal is important to optimize the SEC levels. An increase in metal tapping temperature results in an increase in SEC (Figure 10).

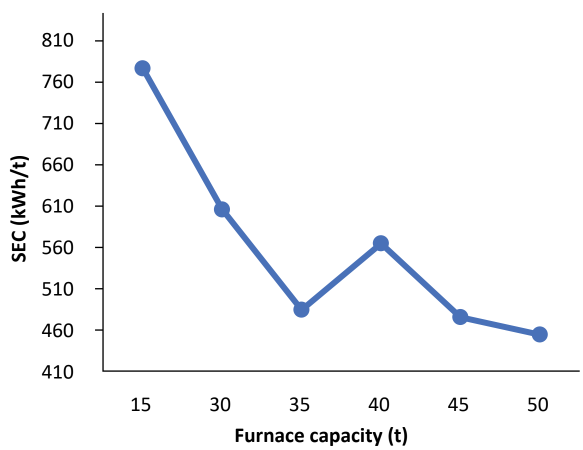


Figure 9: SEC variation with furnace capacity

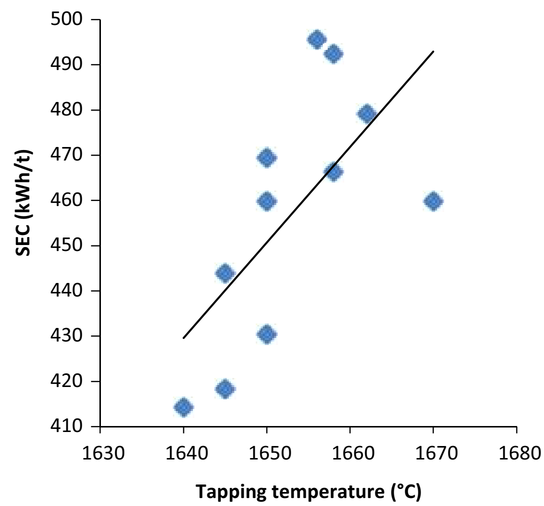


Figure 10: Effect of tapping temperature on SEC

Ideally, an optimally maintained and operated furnace should consume an SEC close to the design value. However, the EAFs in operation among the secondary steel units are found to be higher than this value. The higher energy consumption in an EAF can be attributed to design-related problems of the furnace and/or inefficient operating practices followed. However, in general, the primary reason for high SEC consumption is not sub-optimal design of the furnaces but poor operating practices.

3.4
Productivity

Productivity or melting rate of the furnace is measured by the molten metal produced per hour (tph).

It is a function of time utilization as it influences the energy consumption—the longer the melting time, the larger the EAF thermal loss. For higher productivity, new furnaces should have shorter tap-to-tap times (TTT), i.e., 60 minutes and below. There are many fixed energy losses in furnace operations, some of which include heat removed by the cooling water and radiation heat losses from the furnace body. Reducing the TTT, that is improving the productivity (quantity of steel tapped per unit of time) by increasing the energy input to the furnace leads to better energy performance of the furnace.

3.5
Yield efficiency

The yield efficiency is measured in terms of percentage of the liquid metal output (good product delivered to the rolling mills) compared to the metallic input (sponge iron, scrap, pig iron, returns, etc.). Higher the liquid metal output, the higher is the yield efficiency and vice versa.

The yield of an EAF is dependent on the quality of metallics and operating practices.

The yield of the EAFs operating in the secondary steel sector typically ranges between 85–92%. As can be seen from the Figure 11, the yield of an EAF is a direct function of the furnace capacities. The yield is generally more in large capacity furnaces.

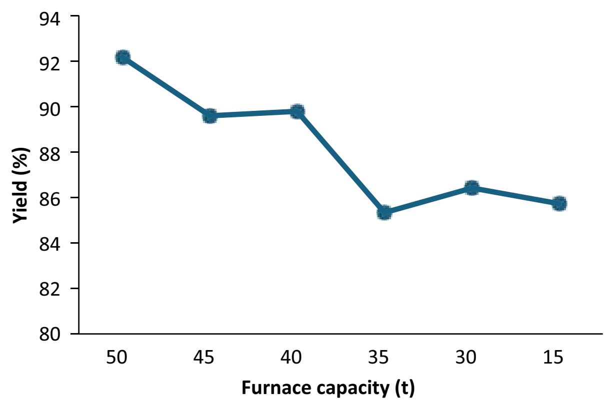


Figure 11: Effect of furnace capacity on yield

04

Energy efficient practices for arc furnaces

The arc furnace accounts for majority (~80%) of the total amount of energy consumed in a standalone EAF-based steel plant. The SEC of EAFs being used by secondary steel producers in India is significantly higher as compared to international benchmark. The electrical energy consumption of an EAF should range between 400–500 kWh/t. However, a variety of factors including impurities in the charge materials and process conditions lead to a higher energy consumption of about 650 kWh/t. Prevalence of conventional, inefficient technologies and operating practices also leads to a higher power consumption.

The following best operating practices are discussed in this chapter.

4.1 Efficient scrap charging and analysis of molten steel

4.2 Utilization of hot DRI/metal

4.3 Lowering molten steel temperature

4.4 Optimum input of power

4.5 Foaming slag practice

4.6 Oxygen enrichment

4.7 Electrode management excellent practices

4.1 Efficient scrap charging practices and analysis of molten steel

Efficient scrap charging practices help maximize heat transfer and minimize energy loss. Proper segregation and charging of scrap in the furnace optimizes heat distribution, reduces the tap-to-tap time (TTT) and also optimizes energy requirement in melting. Charging immediately after tapping can save energy. Modern operations aim for a tap-to-tap time of less than 60 minutes. Some twin shell furnace operations are achieving TTT of 35 to 40 minutes. Hence, it is important to quickly charge the scrap and keep tap-to-tap time to a minimum. Lower TTT can lead to significant reduction in electrical energy consumption in an EAF. Table 10 shows the relation of TTT with specific energy consumption (SEC).

Table 10: Relation of TTT with SEC of EAF

TTT	Specific Energy Consumption
Minutes	kWh/t liquid metal
180	550–650
120	480–520
90	430–470
70	380–420
60	360–400

Souce: Adapted from open report JICA, 2009

Additionally, the sample test must be carried quickly to limit the power consumption on maintaining the molten metal temperature.

4.2 Utilization of hot DRI/metal

Hot metal charging is not commonly practiced among EAFs in India. Hot metal has dissolved carbon and silicon which are important sources of heat of oxidation. The heat of oxidation along with sensible heat available in the hot metal helps to substantially reduce the power consumption of the furnace. Further, hot metal is free of foreign non-metallic materials which would have been removed as slag during iron making process. There is a good potential to charge hot DRI/metal directly into the EAF at a temperature of about 600°C (Voelkar B., *et al.*, 2022). The energy savings from hot DRI charging largely depends on the share of DRI in the charge. Typically, furnaces with 50% hot DRI charging could reduce their energy saving potential upto 150 kWh/t of liquid metal, assuming hot DRI temperature of 600°C. Some of the other benefits of hot metal charging are as follows.

a) Increased carbon content in the charge

b) Enhanced productivity

c) Improved slag foaming

However, the steel plants need to take care of the reactions of the molten metal with oxygen and carbon present in the metal (Tian B. *et al.*, 2022). The hot metal should be charged in a controlled manner to take care of these reactions. Studies show that hot metal, charged between 30–40%, is suitable for EAF (Vishwakarama U.K., Bose P.K. *et al.*). Hot metal charging up to 50% has been successfully used in some of the EAFs. However, hot metal charging more than 50% would result in operational problems as excessive heat is generated through oxidation of elements such as carbon, silicon, and manganese, which will lead to overheating of the furnaces.

Some of the barriers inhibiting the use of hot metal are the unavailability of hot charge and plant layout. Therefore, steel producers having DRI manufacturing as well as EAF within the same facility are best suited to utilize hot DRI in the EAF. Different methods such as pneumatic transfer, electro-mechanical conveyor system, gravity feed and transport in insulated ladles are commonly used to transfer the hot DRI/metal into the EAF. To minimize transportation costs, the DRI plant must be located adjacent to the EAF. Preheating of scrap with waste heat from EAF off-gas prior to charging into the furnace can also reduce energy consumption.

4.3

Lowering molten steel temperature

The amount of energy required to elevate the temperature of steel by 60°C (say from 1540°C to 1600°C) is 12.5 kWh/t. This fact reinforces the importance of controlling the tapping temperature to its minimum required as a practical way to maintain the EAF operating cost. The additional cost in electrical energy consumption for tapping 60°C hotter metal in a 100t EAF could be around ₹9400 in northern India. Therefore, tapping 60°C hot metal can add costs of up to ₹94/t. This added cost not only refers to the electrical energy needed but also takes significant process time to elevate the temperature, and with that, the productivity of the EAF will decrease.

4.4

Optimum input of power

The productivity (molten metal output per hour) of the furnace can be raised by increasing the amount of power input to the furnace. Improving productivity is considered as one of the most effective energy conservation measures. With optimized power input using better regulation system, along with other interventions, the power consumption in an EAF reduced from 475 kWh/t to 430 kWh/t in one of the units in northern India. The average number of heat production also rose to about 19.5 heats per day from 15.5 heats per day in the same unit after interventions (long-term audit feedback).

4.5
Foaming slag practice

Often, adequate foaming occurs at the beginning of the refining process but gradually decreases towards the end of the heat making. At the beginning of melting process, the radiation loss from arc to the side walls is low or negligible. This is because the electrodes are surrounded by scrap which are at low temperatures. In the meltdown phase, the temperature of scrap and melt rises, leading to higher heat radiation from the side walls and higher refractory consumption. Creating a layer of slag (as shown in Figure 12) to cover the arc helps in the following ways:

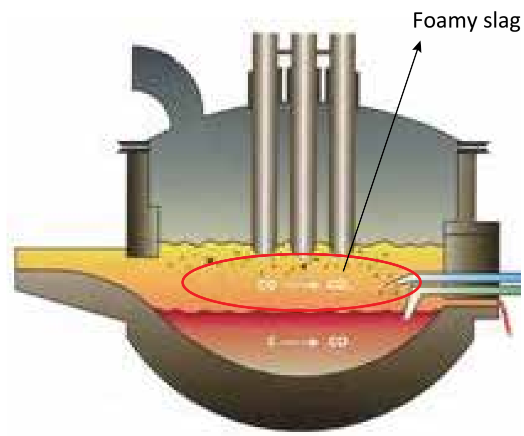


Figure 12: Foamy slag in EAF

Source: D Souza J., 2016

- Improves heat transfer to molten bath
- Minimizes heat loss through side walls
- Decreases electrode and refractory consumption
- Improves arc stability during long arc operations
- Increases melting rate of the furnace

The process of slag foaming involves reactions that generate and sustain gas bubbles along with proper slag. Foaming is done once a flat bath is achieved. In an EAF, oxygen is injected inside along with granular coal or carbon. The carbon reacts with iron oxide (FeO) present in the slag and produces carbon monoxide (CO), which foams the slag. The following reactions result in gas production inside the furnace:

Reaction between FeO of slag with carbon

$(FeO)_l + C \rightarrow [Fe]+\{CO\}$

Reaction between carbon and oxygen dissolved in metal

$[C] + [O] \rightarrow \{CO\}$

Reaction between chromium oxide and carbon (for stainless steel making)

$Cr_2O_3 + 3C \rightarrow 2Cr+3\{CO\}$

It is important to maintain foaming slag throughout refining period to minimize energy losses to the side walls and efficient use of electrical energy inputs. Injection of carbon and oxygen at multiple points in the bath will ensure and enhance slag foaming, when carbon content of the bath is insufficient (*P. Eugene et al., EAF Fundamentals*). Figure 13 and Figure 14 show the effect of foamy slag on heat losses.

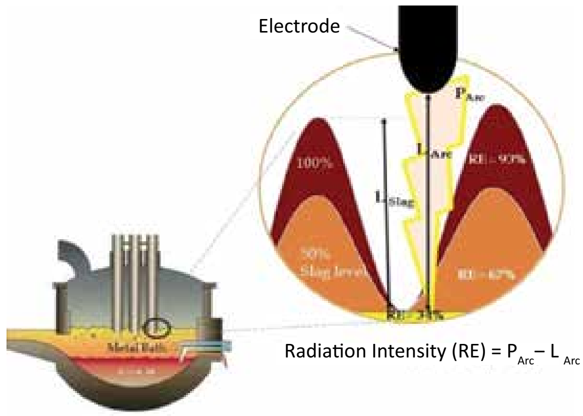


Figure 13: Heat losses to side walls of EAF with foamy slag

Source: D Souza J,2016

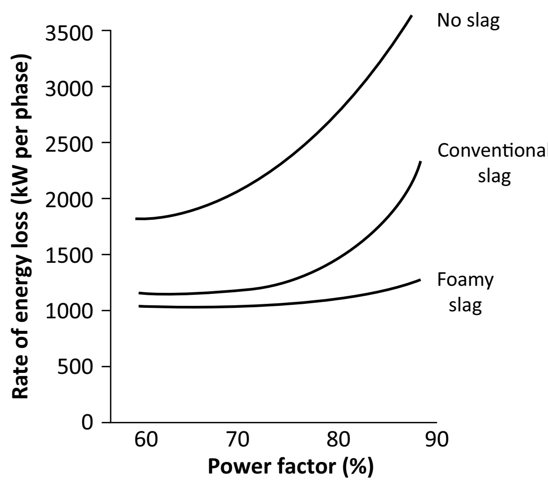


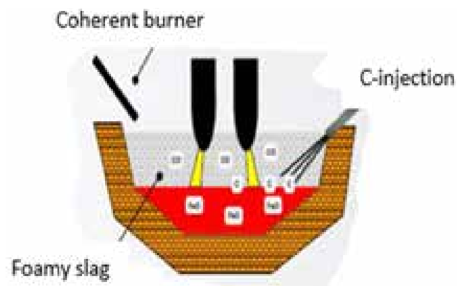
Figure 14: Effect of foamy slag on heat losses

Source: P. Eugene et al., EAF Fundamentals

In an arc furnace, the slag thickness is typically about 4 inches (10 cm). With foaming practice, the slag cover can be increased up to about 12 inches (30 cm), which acts as an insulation cover for molten batch, retaining heat as well as increasing temperature of molten metal bath. Further, with formation of a deep foamy slag, there is a potential to increase the arc voltage significantly, which would allow higher power inputs in the furnace. Box 1 shows the importance of foamy slag practice and chemistry of slag in energy reduction in an EAF.

Box 1: Submerged arc and chemistry of slag

Foamy slag along with right chemistry (Basicity 1.5–2.2, FeO – 15–20%) along with highly efficient burner, controlled O_2 & C injection at right position with sufficient slag thickness with airtight operation and arc shrouded in foamy slag will lead to total energy savings of 2–3%. The electrical energy savings of 6 kWh/t are possible through right practices.



Source: TCL part 2: EAF(v5.0)

4.6

Oxygen enrichment

State-of-the-art electric arc furnaces (EAFs) employ oxygen enrichment through oxy-fuel burners mounted on sidewalls, utilizing fuels such as natural gas or LPG. This approach supplements energy to address cold spots, ensuring uniform bath temperature and consistent melting. Once a liquid metal pool forms, oxygen is directly lanced into the molten bath, accelerating the oxidation of carbon and other solutes, such as silicon, manganese, and phosphorus, present in the raw materials. These exothermic oxidation reactions generate additional thermal energy, further aiding the melting process and facilitating impurity removal through slag formation.

Oxygen enrichment leads to faster melting and shorter cycle times (reduced by 3–6 minutes), resulting in improved yield (by about 1%) EE (Sung Y *et al.*, 2020).

4.7

Electrode management excellent practices

The four key mechanisms contributing to electrode consumption are tip consumption (sublimation losses), sidewall oxidation, stub loss, and top joint breakage (Migas P., Karbowniczek M., 2013). Using high-quality, energy-efficient electrodes along with good practices can improve heat transfer efficiency, reduce power loss and electrode consumption during the melting process. With best operational practices, like better handling of electrodes during transportation and installation, optimized magnitude of current, power-on time, and arc stability, lower electrode consumption can be achieved. One such technique is using higher voltages with lower currents (long-arc operations) leading to lower sublimation losses. Good scrap loading practice can lower joint breakages and electrode automation can provide better control of operations leading to lower electrode consumption.

By utilizing high-quality electrodes and implementing excellent operational practices, one unit in northern India has achieved an electrode consumption rate of approximately 1.2 kg per tonne of steel.


Schneider
Electric

05

Energy-efficient technologies for arc furnaces

The electric arc furnace (EAF) used to produce crude steel from scrap metal and direct reduced iron (DRI) has seen many technological developments in recent years. Electric energy consumption has decreased down to 350 kWh/t for 100% scrap operations. Furnace size has enlarged, and consumption of refractory and electrodes have reduced with the adoption of several new efficient technologies.

The following energy-efficient technologies in EAF are discussed in the chapter.

5.1 Ultra high-power (UHP) transformer
5.2 High impedance system
5.3 Improved regulation control
5.4 Oxy-fuel burner
5.5 Eccentric bottom tapping (EBT)
5.6 Energy optimizing furnace (EOF)
5.7 Zero power furnace
5.8 Bottom stirring system
5.9 Neural network for process control
5.10 Scrap pre-heating system
5.11 Inverter fed AC electric arc furnace

5.1 Ultra High Power (UHP) transformer

The energy losses occurring in a transformer is a function of its age, size and power rating. Classification of transformers (ultra-high, high, medium and low) based on their power rating is given in Figure 15.

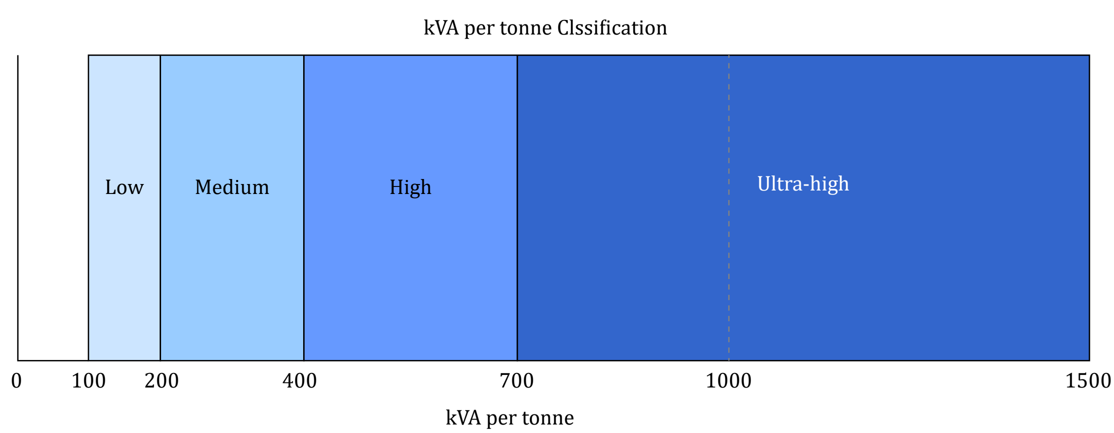


Figure 15: Classification of transformers based on power rating in EAF

Source: Adapted from Lupi S. Fundamentals of Electro-heat

The increased power can be reached by installing a new transformer. The power rating of the transformers commonly prevalent among small and medium secondary steel producers are about 500 kVA/t. As seen from the figure, a transformer is termed as UHP when its power rating is above 700 kVA/t. Transformers with power rating of 1000 kVA/t are commercially available while transformers with power rating of 1500 kVA/t are under development. The benefits of UHP transformers include increased productivity, reduced electrode consumption and lower energy losses. The UHP operation may lead to heat fluxes and increased refractory wear, making cooling of the furnace panels necessary. This results in heat losses that partially offset the power savings.

Typically, for a 50 tonne capacity EAF, the investment required for retrofitting to UHP is about ₹40 million. However, the payback period on investment is estimated to be about 2 years.

5.2

High impedance system

The EAF operation traditionally focuses on short arcs and high currents to transfer maximum power into the furnace, which results in high electrode consumption. The development of foamy slag practice leads to use of longer arc operation. This also leads to lower operational currents and reduced electrode consumption. However, this practice has brought challenges such as higher flickers and harmonics, particularly during the bore down period, thus leading to unstable operations as well as stress on feeding power supply system. It has also resulted in greater stress on mechanical components due to increased vibrations.

The shortcomings in EAF operations can be minimized with high impedance operation. With low current and long arc operation, it is important to select an appropriate power factor and a suitable system reactance for stable operation. Use of high impedance system helps in operating the furnace close to the maximum power point of a given tap and lowers the sensitivity of power changes versus current changes. High impedance is achieved by adding a reactor on primary side of the transformer. Also, the voltage taps on the secondary side of the transformer are raised to compensate for the voltage drop in the reactor. It helps in more stable and smooth operation of the furnace. The major advantages of maintaining high impedance system include the following:

- Reduction in electrode tip consumption and breakage
- Less mechanical forces acting on the electrodes and electrode arms
- Less flickers and lower harmonics distortions on supply network
- Stable arc operations
- Potential to use electrodes of smaller diameter due to lower current which will reduce oxidation losses substantially

The average energy savings with high impedance operation is estimated to be about 1–2%. Typically for a 50-tonne furnace, the investment required for reactor is about ₹17 million with simple payback period of about 3 years (Table 11).

The effect of impedance can be illustrated by considering three cases (a) traditional design, (b) same arc power but with lower electrode current and (c) same arc power and arc length but with slightly lower power factor to stabilize the arcing condition. The furnace can be operated with long arc for about 75% of power on time, and with this assumption the effect of high impedance on operating characteristics of EAF is given in Table 11. Although case 2 and case 3 indicate similar results, the advantage with case 3 is stable arcing operation.

Table 11: Comparison of various impedance systems on EAF

Particular	Unit	Case 1	Case 2	Case 3
Secondary voltage	V	800	1025	1100
System reactance	m Ω	3.3	6.1	7.1
Electrode current	kA	65.3	50.4	50.4
Active power	MW	73.7	71.5	71.4
Arc power	MW	67.8	67.7	67.6
Power factor		0.84	0.83	0.78
Arc voltage	V	363	461	460
Electrode saving	%	-	15	15
Energy saving	%	-	1.5	1.5

Source: Kjell Bergman, Danieli CentroMet, Steel Times International

Moreover, in the UHP transformer-based furnaces, there is an additional risk of tip breakage of electrodes due to high short-circuit currents. The operation at high impedance with slightly lower power factor reduces the short-circuit currents by about a third, thus reducing the tensile stress in the tip of electrode by about 50% (Table 12).

Table 12: Effect of UHP transformer on tensile stress in electrode tip

Particular	Unit	Case 1	Case 2
Nominal current	kA	65	50
Nominal torque on electrode clamp	$Nm10^{-3}$	3.3	6.1
Tensile stress in electrode	MN/m^2	0.39	0.23
Tensile stress in tip of electrode	MN/m^2	5.46	2.46

Source: Kjell Bergman, Danieli CentroMet, Steel Times International

The EAF units installing new transformers are mandated to use UHP transformers along with reactors. Therefore, the overall energy savings would be cumulative of both UHP and high impedance. Many EAF units have already undergone a series of upgradations including installation of high impedance systems.

5.3

Improved regulation control

The degree of transformation of electrical power into thermal energy is pivotal for efficient operation of electric arc furnace. This depends on regulation of transformer, which traditionally uses the following methods (i) changing the number of turns in primary winding, (ii) star to delta switching on primary side of the transformer (this is not applicable for UHP transformers as regulation is done through on-load tap changer), (iii) use of auto transformers, and (iv) booster transformer. One of the major issues with conventional regulation system is that it is a complex-structure contact on-load tap changer, which increases the switching time (3–5 seconds). Further, the on-load tap changer operates in high-intensity mode (frequent changes ~500–800 per day) leading to high wear-and-tear thereby, decreasing the operational reliability.

The shortcomings in conventional regulation systems (analogue/electro-hydraulic) can be addressed with high pressure hydraulic digital regulation. The digital system would allow minimum delays for switching from one melting stage to another. This system can be linked with Level 2 or 3 automation for dynamic production control. The main advantages of digital based regulation system are the following:

- Reduction in tap-to-tap time
- Increase in productivity
- Increase in operational reliability

The average energy savings with improved electrode regulation is estimated to be about 3%. Typically for a 50-tonne furnace, the investment requirement is about ₹7.5 million which includes hardware and software and associated hydraulic systems. The simple payback period is about 6 months.

The units having digital electrode regulation system can achieve additional energy savings by fine-tuning their software with respect to the scrap quality. Many EAFs have upgraded their regulation control system with more precise and faster servo motor systems leading to better productivity and reduction in specific energy consumption.

5.4
Oxy-fuel burner

The EAF operation is characterized by a pattern of hot and cold spots across the furnace cross-section. The cold spots exist generally in the areas lying between electrodes on the peripheral areas of furnace bottom. The creation of cold spots within the EAF would lead to increase in tap-to-tap time thereby, increasing the specific energy consumption. It is therefore important to eliminate cold spots from the furnace. Oxygen injection—either lancing or oxy-fuel burner would help in addressing the issue related to cold spots. Figure 16 shows oxy-fuel burner in an EAF.

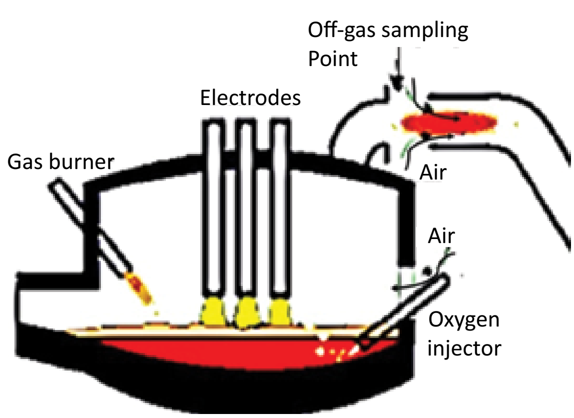


Figure 16: Oxy-fuel burner

Source: K. Marcus et al.

State-of-the-art EAFs are equipped with oxy-fuel burners mounted on the sidewalls. Natural gas, LPG, etc., are used in oxy-fuel burners. The oxy-fuel burners are used to provide additional energy to cold spots, thereby ensuring homogeneity of liquid bath temperature leading to a more uniform melting. Upon formation of liquid metal pool, oxygen can be directly lanced into the molten bath to accelerate oxidation of various solutes, starting with carbon in the bath and iron. Figure 17 shows relation of electricity consumption with oxygen consumption in an EAF.

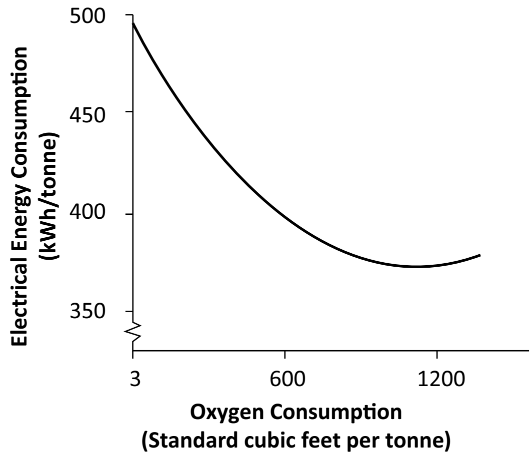


Figure 17: Variation of electricity consumption with oxygen use (100 tonne EAF)

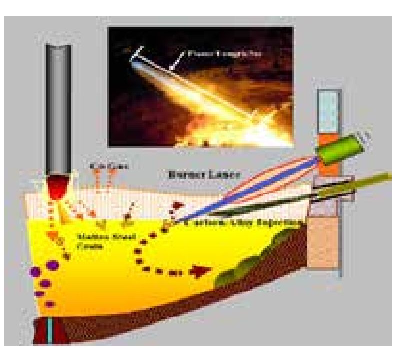
Source: CMP, Carnegie Mellon research institute

During this process, silicon, manganese, and phosphorus present in the raw materials also get oxidized and are removed as slag. These reactions are exothermic thereby, provide additional thermal energy for melting. The reaction of oxygen with carbon in the bath forms carbon monoxide (CO). This CO either burns in the furnace if sufficient oxygen is available or exhausted through fume extraction system wherein it is combusted and sent to pollution control system. The CO escaping from the bath produces carbon boil in the melt, which helps in (i) heat transfer by agitating the molten bath, (ii) cleansing the bath of retained oxides during de-slagging, (iii) accelerating reactions at the gas metal interface and (iv) aiding in removal of hydrogen and nitrogen formed during the reactions.

Box 2 provides an overview of high efficiency oxy-fuel burners for EAF.

Box 2: High efficiency oxy-fuel burner/lancing for EAF

New type of burner has been used to inject carbon and oxygen from side wall and closed slag door. The burner can realize evenly distributed slag-foaming and coherent burner can make long and sharp oxygen jet, which works instead of oxygen lance. Oxygen jet from the center hole is restricted to expand by the combustion around the jet, the combustion is generated by the fuel and oxygen from peripheral inlets.



Schematic diagram showing high efficiency oxy-fuel burner in an EAF

Photograph showing cross section of a high efficiency oxy-fuel burner

Source: TCL part 2: EAF (v5.0), JISF 2023

Modern EAF units widely use wall-mounted oxy-fuel burners and a combination of lance-burners. These burners operate in a burner mode at the beginning of melting. Upon formation of liquid metal, the burners change over to lancing mode. Some of the important advantages of using oxy-fuel burners include:

- Lower electricity consumption (Sung y *et al.*, 2020)
- Reduction in tap-to-tap time (3–6 minutes)
- Enhancement of yield by about 1%

The average energy savings by installation of oxy-fuel burners is estimated to be about 3%. Typically for a 50 tonne furnace, the investment required for the installation is about ₹40 million with a simple payback period is about 2 years.

5.5
Eccentric bottom tapping (EBT)

Tapping in EAF is done either by spout or through a tap hole at bottom. In case of spout tapping, the furnace is tilted, and the steel pours into a ladle for next operation (generally a ladle furnace). This can lead to slag carryover in the ladle, loss of metal, loss of refractory and higher tapping time.

Molten steel can also be tapped through the hole at the bottom of furnace. The tilting angle for tapping is smaller than conventional spout tapping; also, quick tapping and returning are possible in the system. The tapping hole is plugged with silicon sand after tapping, which is held by stopping mechanism. Thus, slag free tapping is possible along with lower tapping time, and increased yield by upto 1.1%.

The savings from eccentric bottom tapping (EBT) can be multifold. Apart from energy savings, there is potential to increase yield of alloys, iron and improved steel quality. The power consumption can reduce from 7–25 kWh/t. The potential benefits are summarized in Table 13.

Table 13: Potential benefits of EBT

S.no.	Parameter	Improvement potential	Remarks
1	Yield of alloys	Si: Increase from 15–100%	Slag free tapping
2	Yield of Fe	Increase by 1.1%	Due to slag free tapping and hot heel
3	Electrical power consumption	Reduction by 7–25 kWh/t	Hot heel
4	Electrode consumption	Reduction by 0.2–0.4 Kg/t	Due to decrease of electrical power and high-power factor
5	Refractory consumption	Furnace wall—Decrease by 23–64% Ladle Wall: 9–54%	Due to increase in water cooled area and slag free tapping
6	Lime consumption	Reduction by 15–25%	Hot heel
7	Tap-to-On time	Reduction by 1–3 min	Shortened hot repair and time for tilt tapping, decrease in electrode consumption
8	On-to-tap time	Reduction by 1–7 min	
9	Phosphorus in metal	Reduction by 16–28%	Hot heel
10	Inclusion	Total [O] reduction by 1–3 ppm	Slag free tapping

S*ouce: TCL part 2: EAF (v5.0), JISF 2023*

5.6 Energy optimizing furnace (EOF)

EOF was developed to utilize the sensible heat of small and medium-sized steel converters in an effective way. EOF is a combination of three independent, interconnected reactors namely, furnace to produce steel, preheater to heat the scrap, and a recuperator to recover waste heat.

EOF leverages the heat generated from the oxidation of solutes (like carbon and other elements) in hot metal to produce steel, making it an energy-efficient process. The EOF process involves combining hot metal, scrap, and DRI along with a combined blowing basic oxygen steelmaking process. Oxygen is blown through submerged tuyeres and supersonic lances to oxidize the solutes and produce steel. The EOF process is known for its high productivity, fast decarburization and dephosphorization rates, and ability to achieve low blowing times (around 25–30 minutes).

A typical schematic of EOF is shown in Figure 18.

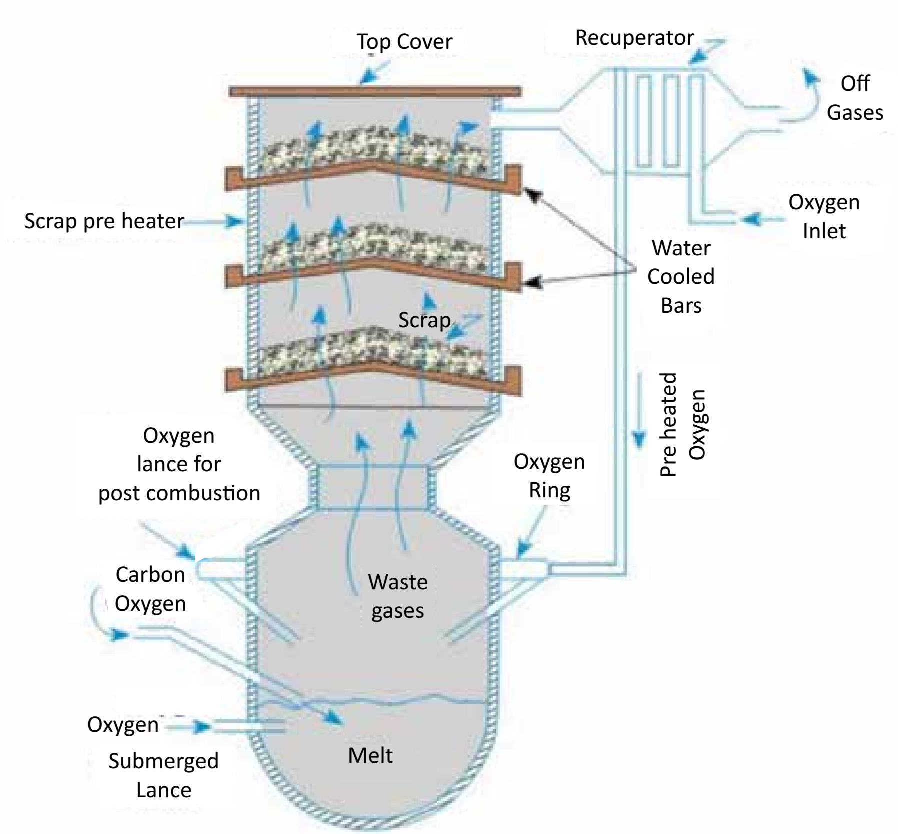


Figure 18: Typical energy optimizing furnace

Source: Emerging Steelmaking Technologies, NPTEL

JSW Steel has implemented a 65 tonne EOF at its Salem plant, which is considered the world's largest of its kind (R. Marappan *et al.*, 2008). It is an EAF combined basic oxygen steel making process where a mix of hot metal, scrap and DRI forms the charge.

5.7
Zero power furnace

A zero (electric) power furnace (ZPF) allows for steel production without relying on electrical energy. The furnace uses liquid hot metal and chemical energy generated by oxidation. The technology, also called new oxygen furnace (NOF), has the flexibility of converting various charge mix of raw material – from 100% DRI to 90% hot metal into steel efficiently. The technology leads to higher yield and productivity with minimum consumption of the electrode. The furnace is highly adaptable and can be converted from ZPF/NOF to normal EAF and vice versa in a short span (less than 24 hours).

Some of the large-scale steel plants like JSW Steel and JSPL have implemented the technology.

5.8
Bottom stirring systems

The molten metal in the arc furnace may not be of homogenous mass or uniform quality across the cross-section. Improper thermal and chemical bath homogeneity directly affect the refractory performance. This may result in skull formation, cold spots near EBT, unbelted input material, unreliable sampling results and so on. Better homogenization of the liquid metal bath is hence required to overcome the issues and enhance productivity. Bottom stirring of the liquid bath in the EAF is an effective solution to enhance homogenization and ensure consistent quality.

The following types of bottom stirring systems are discussed in this section:

- Electro-magnetic stirring
- Inert gas stirring

5.8.1
Electro-magnetic stirring

The electro-magnetic stirrer (EMS) by ABB represents a next generation stirring system designed for EAFs. With its high intensity stirring capability, EMS improves the melting of large scrap pieces and reduces stratification through forced convection. The enhanced convection facilitates a more uniform temperature distribution, accelerates the melting process, and ultimately contributes to reduced tap-to-tap time in liquid steel production.

Adoption of EMS could lead to several benefits including lowering energy costs, savings in refractory materials, faster scrap melting and lower electrode consumption. Energy savings in the range of 3–5% have been reportedly achieved by EAF plants by the adoption of the technology, in addition to 6–10% fall in wall refractory consumption and an increase in productivity by 5–7% (Electromagnetic stirring, ABB).

5.8.2
Inert gas stirring

Inert gas stirring is established as the most common method for improving process control, energy efficiency, metal yield, and process time in EAFs. Bottom stirring of liquid bath in EAF is a potential solution for better homogenization and ensure uniform quality.

In an inert gas stirring system, the stirring of liquid metal is accomplished using inert gases such as argon or nitrogen (as shown in Figure 19). Bottom stirring systems based on inert gas injection are available either as a single tube or multi-hole plugs. These plugs are either buried in the furnace hearth ramming mix or indirect purging or in contact with steel melt or direct purging. Indirect purging arrangement offers improved stirring arrangement due to better distribution of inert gases (K Marcus ***et al.***, 2015).

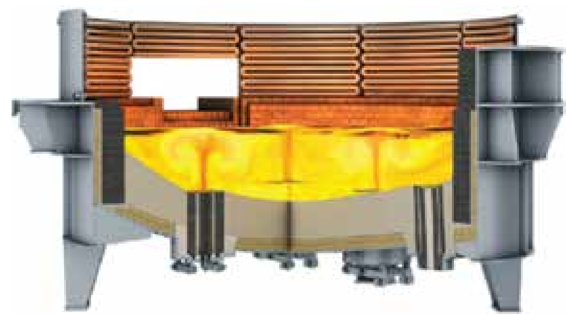


Figure 19: Inert gas stirring system

Source: RHI Magnesia

Figure 20 shows direct and indirect stirring systems. Bottom stirring further accelerates chemical reactions between steel and slag.

Investment in inert gas purging can lead to energy savings between 5–30 kWh/tonne and an attractive return on investment for a few months.

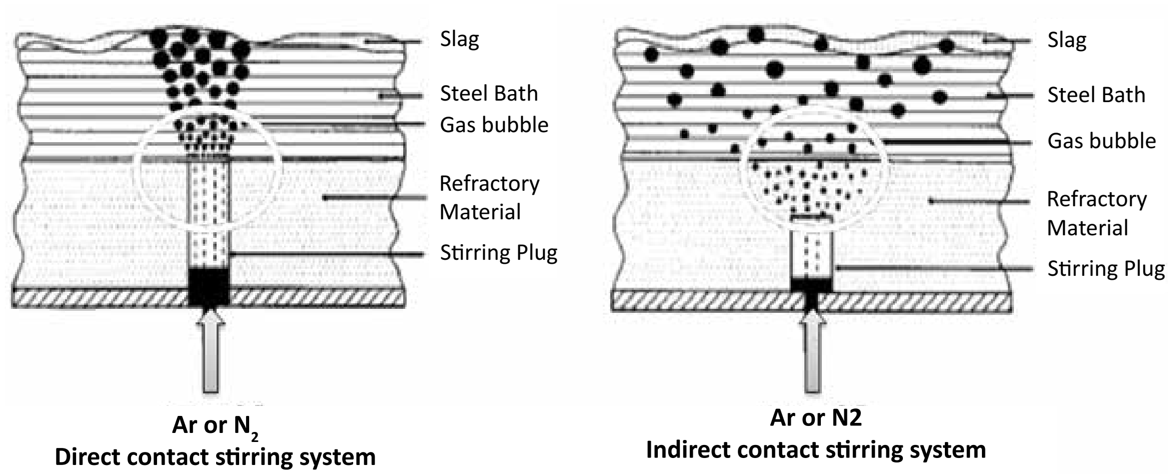


Figure 20: Direct and indirect stirring systems

Source: Lupi S., 2017

5.9

Neural network for process control

There are several complex physical changes and chemical reactions under high-temperature conditions taking place in an EAF. Neural network for process control has the advantage of intelligently mining patterns from massive data and optimizing furnace operation.

Advanced electrode regulation system can lead to improved furnace performance. Recent advancements have led to the use of artificial intelligence-based electrode controllers. Intelligent data processing with neural networks offers a better solution for electrode regulation system. These intelligent systems integrate real-time monitoring of process variables, such as liquid metal temperature, carbon percentages and oxygen lancing practices. The systems have been upgraded to level 1 and 2 automation systems in many cases as per the feasibility and lead to better productivity.

The average energy savings with neural network-based EAF electrode regulation system is estimated to range between 3–5%.

5.10
Scrap pre-heating systems

In an EAF between 15–20% of input energy is carried away by the off-gases. This waste heat can be effectively recovered using scrap pre-heating systems, which significantly reduce the overall energy consumption of the furnace. Integrating scrap pre-heating with EAF operations enhances efficiency, lowers energy costs, and improves overall process sustainability.

There are two major types of scrap pre-heating system:

- Bucket type pre-heating system
- Shaft type pre-heating system

5.10.1
Bucket type pre-heating system

The bucket pre-heating system has been traditionally used with EAF. In this system, the specially designed scrap charging buckets are equipped with burners or heat recovery mechanisms (as shown in Figure 22). The off-gases from the EAF are routed through the scrap charging bucket in a counter flow direction. However, limitations of bucket type pre-heating system are:

- Limited pre-heating efficiency due to heat loss during transfer
- Requires precise burner control to avoid excessive oxidation
- Poor heat recovery and operational and maintenance issues

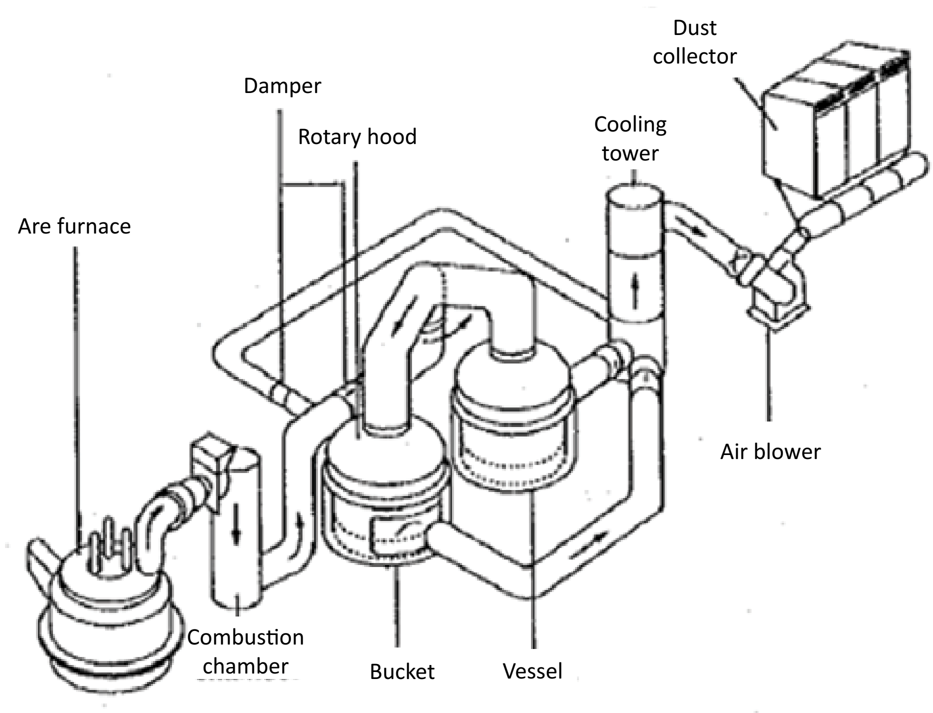


Figure 21: Conceptual design of bucket type scrap pre-heating system

Source: Open report – JICA

5.10.2
Shaft type pre-heating system

A shaft pre-heating system consists of a vertical pre-heating chamber positioned above the EAF, where hot exhaust gases from the furnace are recirculated to pre-heat scrap material as it moves downwards into the furnace. The scrap is charged into the furnace through the shaft. This will lead to better heat recovery.

A version of this type of pre-heating system is the ECOARC™ developed by JP Steel Plantech Co, Japan (Figure 22). This system has no mechanism to hold charged scrap in the shaft such as a finger. As a result, scrap at the bottom of the shaft is always in contact with molten steel in the melting furnace. During operation, scrap is fed to the furnace from the top of the shaft. Accordingly, except cold start, the melting process undergoes so-called flat bath condition. Even in super heating and tapping periods, the shaft keeps certain amount of scrap for pre-heating. In this system, the scrap is supplied semi-continuously during the heat. Use of low bulk density scrap such as turnings are advised for effective heat recovery.

A similar technology, known as Consteel® technology by Tenova. Consteel® is a continuous, horizontal preheating system that feeds scrap into the Electric Arc Furnace, enhancing energy efficiency and productivity.

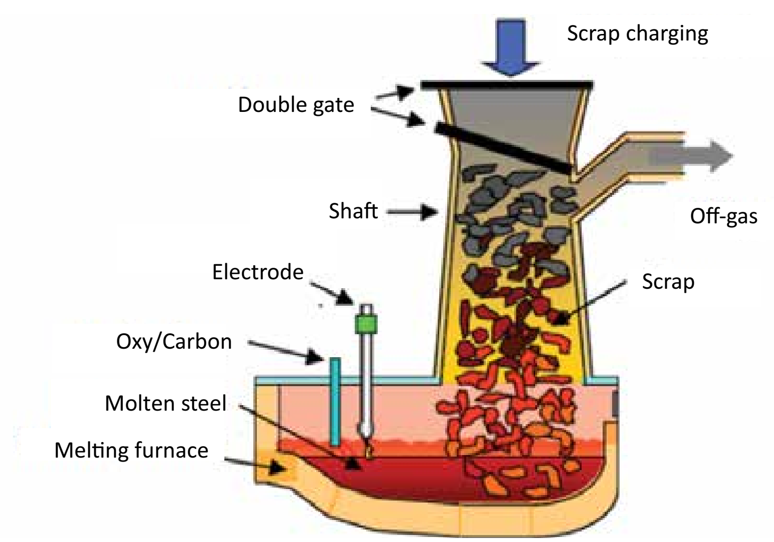


Figure 22: Shaft type pre-heating system

Source: Nagai T. et al., ECOARC

5.11
Inverter fed AC electric arc furnace

The electric arc furnace can only be operated up to a certain power factor and has high reactive power. The electrical equipment can therefore not be used optimally. This high reactive power often leads to repercussions on grid in the form of flicker.

In an inverter fed AC electric arc, an electrical arrangement of the type mentioned is configured in a fashion that the furnace transformer is not only connected to the output side of the electrodes of the arc furnace, but also to the capacitor arrangement. The capacitor arrangement is not arranged on the primary side of the furnace transformer or even further towards the supply network as in conventional systems but on the secondary side of the furnace transformer. Furthermore, the control device maintains the furnace frequency at least ten times the mains frequency and/or greater than 1 kHz. This refinement controls reactive power between the supply network and the converter, the converter and the furnace transformer and on the output side of the furnace transformer. Therefore, no further reactive power compensation is required. Rather, it is possible to adjust the supply by the converter in such a way that the electric oscillating circuit formed by the electrodes of the arc furnace and the capacitor arrangement is excited to resonate. Modern systems use power electronics to handle reactive power issue.

This technology has potential to save around 10% process energy. Also, there are other potential benefits like reduction of electrode consumption by about 20% and reduction of power-on time by about 10% and 10% reduction in noise levels (Q-ONE – Danieli Automation). A comprehensive list of technology suppliers and vendors offering energy-efficient solutions can be found in Annexure 3.

Consteel® technology by Tenova

Pic credits : Tenova

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Annexures

Annexure 1: EAF units across India

Location wise EAF units

Plant_Name	Industry	Capacity – JPC (In '000 Tonnes)	Plant_State	District
Aarti Steel Ltd – Odisha	EAF	200	Odisha	Cuttack
Aarti Steel Ltd – Punjab	EAF	118	Punjab	Ludhiana
Arcelor Mittal Nippon Steel India Ltd – Surat	EAF	9600	Gujarat	Surat
Arjas Modern Steels Private Ltd	EAF	125	Punjab	Fatehgarh Sahib
Arora Iron and Steel Rolling Mills	EAF	294	Punjab	Ludhiana
Bhilai Engineering Corporation Ltd	EAF	10	Chhattisgarh	Durg
Jsw (Bhushan Power and Steel Ltd – Odisha)	EAF	2750	Odisha	Sambalpur
Evonith Value Steels Limited	EAF	1000	Maharashtra	Wardha
Graphite India Limited Powmex Steels Division	EAF	6	Odisha	Balangir
Ismt Limited	EAF	350	Maharashtra	Pune
J S W Steel Ltd – Vijaynagar	EAF	2000	Karnataka	Bellary
Jayaswals Neco Inds Ltd	EAF	1188	Chhattisgarh	Raipur
Jindal Stainless (Hissar) Ltd – Haryana	EAF	780	Haryana	Hisar
Jindal Stainless Ltd – Odisha	EAF	1100	Odisha	Jajpur
Jindal Steel and Power Ltd – Chhattisgarh	EAF	3600	Chhattisgarh	Raigarh
Jindal Steel and Power Ltd – Odisha	EAF	1500	Odisha	Angul
Jsw Ispat Special Products Ltd-Raigarh	EAF	1500	Chhattisgarh	Raigarh
Jsw Steel Ltd – Dolvi Plant	EAF	5000	Maharashtra	Raigad
Mukand Ltd	EAF	310	Maharashtra	Thane
Panchmahal Steel Ltd	EAF	150	Gujarat	Panchmahals
Saarloha Advanced Materials Pvt Ltd	EAF	204	Maharashtra	Pune
Sail – Alloy Steels Plant	EAF	234	West Bengal	Bardhman
Sail – Salem Steel Plant	EAF	180	Tamil Nadu	Salem

Plant_Name	Industry	Capacity – JPC (In '000 Tonnes)	Plant_State	District
Sanyo Special Steel Manufacturing India Private Limited	EAF	240	Maharashtra	Raigad
Shyam Steel Industries Ltd – Angadpur – West Bengal	EAF	240	West Bengal	Bardhman
Star Wire (I) Ltd	EAF	22	Haryana	Faridabad
Star Wire (India) Ltd – Ii	EAF	45	Haryana	Faridabad
Sunflag Iron and Steel Co. Ltd	EAF	525	Maharashtra	Bhandara
Surya Alloy Industries Ltd	EAF	77	West Bengal	Bankura
Tata Steel Long Products Limited	EAF	1000	Jharkhand	Saraikela
Tata Steel Meramandali	EAF	2000	Odisha	Dhenkanal
Texmaco Rail and Engg Ltd	EAF	30	West Bengal	North 24 Parganas
Vardhman Special Steels	EAF	225	Punjab	Ludhiana
Vossloh Beekay Castings Ltd	EAF	5	Chhattisgarh	Durg

Source : JPC, 2024

Annexure 2: Energy performance assessment

The following outlines the basic method for quantifying the performance and energy losses of electric arc furnaces. This methodology can be used for performance assessment of furnace periodically. The assessment of furnace and its associated auxiliaries should be conducted at normal plant load operation. Ideally, all heat inputs to the furnace should be utilized towards melting of the metal; however, in practice several energy losses occur within the system, leading to deviations in system performance. These losses are summarized below.

Heat loss in off-gases: The off-gases resulting from various chemical reactions occurring inside the furnace exit at quite high temperatures (900–1100°C), which account for major heat loss in an electric arc furnace.

Heat loss in off – gases = $m \times C_p \times (T_g - T_a)$

m Quantity of off-gases (kg/heat)

C_p Specific heat of gases (kcal/kg °C)

Tg Temperature of off-gases (°C)

Ta Ambient temperature (°C)

Heat loss in cooling water: The furnace needs to be cooled continuously during operation in order to maintain the sidewall and roof temperatures within the permissible limits. Any increase in temperature of furnace walls can lead to damage to refractories. Further, the temperature of off-gas needs to be brought down using cooling water before entering bag filters, where temperature is a limiting factor.

Heat loss in cooling water = $m \times C_w \times (T_{out} - T_{in})$

m Quantity of cooling water (kg/heat)

C_w Specific heat of water (kcal/kg °C)

T_{out} Outlet temperature of cooling water (°C)

T_{in} Inlet temperature of cooling water (°C)

Heat in slag: The melting operation forms a sizeable quantity of slag. The slag comprises oxides of Si, Mn, Ca, Fe and Al along with other impurities present in charge material. This slag is removed at very high temperatures leading to substantial heat losses.

Heat loss in slag = $[mC_{pL} \times (T_m - T_a)] + (m \times L) + [mC_{pL} \times (T_s - T_m)]$

m Quantity of slag (kg/heat)

C_{ps} Specific heat of solid slag (kcal/kg °C)

C_{pL} Specific heat of liquid slag (kcal/kg °C)

T_m Melting point of slag

T_s Temperature of slag (°C)

T_a Ambient temperature (°C)

L Heat required for phase transition (kCal/kg)

Heat losses through openings: Radiation and convection heat losses occur from openings present in the furnace and through air infiltration due to furnace draft. The main opening in furnace is slag door, which is kept open throughout the heat in most units.

Heat loss through opening =F_b ×E ×F ×A

E Emissivity of the surface

F_b Black body radiation at furnace temperature (kcal/kg/cm^2/hr)

F Factor of radiation

A Area of opening (cm^2)

Surface heat loss: The heat from furnace surfaces such as sidewalls, roof, etc., are radiated to the atmosphere. The quantum of surface heat loss is dependent on the type and quality of insulation used in furnace construction. The surface heat loss per sq m area can be estimated using:

$$\boldsymbol{Surface\ heat\ loss\ = a \times (Ts - Ta)^{\frac{5}{4}} + 4.88E \left\{ \left(\frac{Ts\ + 273}{100} \right)^4 - \left(\frac{Ta\ + 273}{100} \right)^4 \right\}}$$

a Factor for direction of the surface of natural convection ceiling

Ts Surface temperature (°C)

Ta Ambient temperature (°C)

E Emissivity of external wall surface of the furnace

The total energy losses are sum of all the losses occurring in the furnace.

Furnace efficiency: The efficiency of furnace is evaluated by subtracting various energy losses from total heat input. For this, various operating parameters pertaining to different heat losses must be measured, e.g., energy consumption rate, heat generated from chemical reactions, temperature of off-gases, surface temperatures, etc. Data for some of these parameters can be obtained from production records while others must be measured with special monitoring instruments.

Furnace efficiency = (Total heat input – Total energy losses)/ Total heat input

Annexure 3: EE Technology Vendors

The energy performance improvement in EAF sector would require substantial modifications and adoption of state-of-the-art technologies that are commercially available either in India or at global level. A selected list of technology vendors providing services pertaining to various aspects of energy efficiency in electric arc furnace and the associated auxiliary systems are provided below.

Vendor	Contact Details
Complete EAF package supplier (including regulation control, scrap pre-heating systems and neural network for process control)	
Primetals Technologies India Pvt. Ltd	5th Floor, Tower – C, DLF IT Park-I, 08 Major Arterial Road, New Town (Rajarhat), Kolkata- 700156, West Bengal Tel.: +91 (33) 6629 1000 Fax: +91 (33) 6629 1300
Sarralle, Spain	Av. Tren Expreso Parcela 223 34200 Venta de Baños (Palencia) – Spain Tel.: +34 979 761220 Fax: +34 979 761223 Email: sarralle@sarralle.com
Danieli India Ltd	Technopolis 5th Floor, Wing B, Block BP, Plot IV, Sector V, Salt Lake, Kolkata – 700091, West Bengal Tel.: +91 33 7101 6202 Email: info@india.danieli.com
SMS India Pvt. Ltd	286 Udyog Vihar, Phase II Gurugram- 122016, Haryana Tel.: +91-124 435 1500 and +91-124 435 1703 Email: info-india@sms-group.com
Tennova Melt Shops	Via Monte Rosa, 93, 20149 Milan – Italy Tel.: +39 02 4384 7945 Fax +39 02 4384 7695 Email: meltshops@it.tenovagroup.com
JP Steel Plantech Co.	Yokohama Connect Square 13F 3-3-3 Minatomirai, Nishi-ku, Yokohama, Kanagawa 220-0012, JAPAN Tel : +81-45-612-8470
Prowess International Pvt. Ltd	A-18, 6th phase, Industrial area, Adityapur, Jamshedpur-832108, Jharkhand Tel.: +91-657-2203441 E-mail: info@prowessinternational.co.in
Doshi Technologies Pvt. Ltd (Formerly Doshi & Associates)	863/6- G.I.D.C. Makarpura, Vadodara, Gujarat Tel: +91- 2652634985 Fax: +91 – 2652634984 Email: doshi@doshiassociates.net

Vendor	Contact Details
Energy Optimizing Furnace	
MiniTec	Centralina Street, 190 – 2nd floor – Bom Pastor – Divinópolis -MG – ZIP Code: 35500-147, Brazil Tel.: + 55 37 3222-7113 Email: minitec@minitec.eng.br
Ultra-High Power Transformer	
Siemens	Birla Aurora, Level 21, Plot No. 1080, Dr Annie Besant Road, Worli, Mumbai – 400030, Maharashtra Tel.: +91 022-39677000 Fax: +91 (022) 24362404
ABB Ltd	A-6, Safal Profitaire, Corporate Road, Opp. Ramada Hotel, Ahmedabad – 380051, Gujarat Tel.: +91 96 2436 0600
GE Grid Solutions	Worldwide contact center Web:- www.GEgridsolutions.com/contact Tel.: +44(0) 1785 250 070
Makpowerz Trans-systems	62/F, JN Mukhrjee road, Shed no. 10A, Hanuman Jute mill complex, Ghuari Hawrah – 711107 Tel.: +91 9830917300 Email: maktrafo@yahoo.com, info@makpowerts.com
Tamini transformatori S.r.l.	Viale Cadorna, 56/A – 20025 Legnano (Milano) – Italy Tel.: +39-0298205100
Oxy-Fuel Burner	
Linde Engineering India Pvt. Ltd	Linde House, Opp. VUDA Office, VIP Road, Karelibaug, Vadodara – 390018, Gujarat Tel.: +91 2653056789 Email: india@linde-le.com
American Combustion	ACI Holding LLC, One Alliance Center, 3500 Lenox Rd NE, Suite 1500, Atlanta, GA 30326 Tel.: +1 678 778 7762 Email: vivek.gautam@americancombustion.com
Bottom Stirring – Electromagnetic Stirring	
ABB India Limited	Mr Raghu Badrinathan Area Sales Manager – Metallurgy products Disha – 3rd Floor, Plot No. 5 & 6, 2nd Stage, Peenya Industrial Area IV, Peenya, Bengaluru- 560058, Karnataka Tel.: +91 9901491170, +91 80 22949129 Email: raghu.badrinathan@in.abb.com

Vendor	Contact Details
Scrap Processing	
Vezzani S.p.A.	Piazza Nervi 1, 15076, Ovada (AL), Italy Tel.: +39 0143 81844 Fax: +39 0143 823069
Variable Frequency Drives	
ABB India Limited	5th Floor, A-6 Safal Profitaire, Corporate Road, Ahmedabad, Gujarat Tel.: +91 96 2436 0600
Siemens India Ltd	Birla Aurora, Level 21, Plot No. 1080, Dr Annie Besant Road, Worli, Mumbai – 400030, Maharashtra Tel.: +91 022–39677000 Fax: +91 (022) 24362404
Energy Efficient Pump	
KSB Pumps Limited	KSB Pumps Ltd, KSB House, A-96, Sector IV, Dist Gautam Budh Nagar, Noida – 201301, Uttar Pradesh Tel.: +91 20 2710 1000 Fax: +91 120 2550 567 Email: contactusksbindia@ksb.com
Kirloskar Brothers Limited	C/o 'AWFIS Working Spaces', L29-L34, 1st Floor, Connaught Place, New Delhi 110001 Tel.: +91 011 – 41500040 Email: delhi@kbl.co.in
Grundfos Pumps India Pvt. Ltd	118, Rajiv Gandhi Salai, Ellaiamman Nagar, Thoraipakkam, Chennai 600097, Tamil Nadu Tel.: +91 44 4596 6800 Fax: +91 44 4596 6969 Email: contact.india@sales.grundfos.com

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Creating Innovative Solutions for a Sustainable Future

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